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USAF DURABILITY DESIGN HANDBOOK: GUIDELINES FOR THE ANALYSIS AND DESIGN OF DURABLE AIRCRAFT STRUCTURES

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S. D. Manning

General Dynamics Corporation
Fort Worth Division
P.O. Box 748
Fort Worth, Texas 76101

J. N. Yang

United Analysis Incorporated
2100 Robin Way Court
Vienna, Virginia 22180

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WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-6553

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This technical report has been reviewed and is approved for publication.

FOR Margery E. Artley
Project Engineer

JAMES L. RUDD, Tech Manager
Fatigue, Fracture & Reliability Gp
Structural Integrity Branch

FOR THE COMMANDER

TONY G. GERARDI, Chief
Structural Integrity Branch
Structures Division

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This is the second edition of the Durability Design handbook for metallic airframes. In the first edition of ~~the~~ handbook the probabilistic-based durability analysis methodology was limited to relatively small fatigue cracks (e.g., ≤ 0.1") associated with functional impairment due to excessive cracking. The original durability analysis methodology has been refined and extended to also cover large through-the-thickness cracks (e.g., 0.5"-0.75") associated with functional impairment due to fuel leaks and ligament breakage. Objectives of this handbook are to: 1)

Objectives of the handbook are: (1) summarize and interpret the essential USAF U.S. Air Force Durability Design requirements for metallic airframes; (2) provide durability analysis criteria for economic life and durability-critical parts; (3) provide state-of-the-art durability analysis concepts and

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Margery E. Artley	(513) 255-6104	AFWAL/FIBEC

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18. (continued) probability of crack exceedance, cumulative distribution of service time.

(and)

19. (continued) methods for determining the initial fatigue quality of fastener holes, the probability of distribution of service time to reach any specified crack size; (4) provide guidelines and design data for implementing the durability analysis method and for assisting contractor and USAF personnel in complying with the intent of the durability specifications for metallic airframes. The method

The durability analysis methodology developed provides a ~~durability~~ design tool for quantitatively reflecting durability requirements in the design process and for making design tradeoffs. The method~~ology~~ accounts for the initial fatigue quality variation, crack growth damage accumulation in a population of structural details (e.g., fastener holes, lugs, fillets, cutouts, etc.), load spectra and structural properties.

During manufacturing and assembly, flaws of various types (e.g., scratches, burrs, microscopic imperfections, etc.) are produced in structural details such as fastener holes, cutouts, etc. The initial fatigue quality of such details is represented by an equivalent initial flaw size distribution (EIFSD). An equivalent initial flaw size (EIFS) is an artificial crack size which results in an actual crack size at an actual point in time when the initial flaw is grown forward. EIFSs are determined by back-extrapolating fractographic results. (edc)

The EIFSD is the "cornerstone" for the durability analysis. Once the EIFSD has been determined, a two-segment deterministic-stochastic crack growth approach is used to grow the EIFSD forward to determine either the probability of crack exceedance at any service time and/or the cumulative distribution of service time to reach any specified crack size x_1. The predicted probability of crack exceedance can be used to estimate statistically the "extent of damage" for the durability-critical component. These include the average and upper bound limit of the "extent of damage" for selected exceedance probabilities.

A durability analysis methodology has been developed. Theoretically, it applies to any type of structural detail in a metallic structure. The methodology has been demonstrated for straight-bore and countersunk fastener holes with clearance-fit fasteners in 7475-T7351 aluminum. A comprehensive demonstration has been conducted for coupon specimens and for a full-scale lower wing skin for a fighter aircraft. Applications for other structural details (e.g., cutouts, fillets, etc.) need to be investigated. Also fastener holes with interference-fit fasteners, cold-working, etc., need to be investigated.

The data for defining the initial fatigue quality for different materials and structural details can be acquired economically and timely as a part of the Aircraft Structural Integrity Program (ASIP). Structural details in selected test specimens should not be preflawed so that baseline data can be obtained to satisfy the data requirements for initial fatigue quality, durability and damage tolerance.

FOREWORD

The second edition of this handbook was prepared by General Dynamics (Fort Worth Division) and by United Analysis Incorporated (Vienna, VA) under Phase III Task VIII of the "Advanced Durability Analysis" program (Air Force Contract F33615-84-C-3208) for the Air Force Wright Aeronautical Laboratories (AFWAL/FIBEC). Marge E. Artley was the Air Force Project Engineer. James L. Rudd and Dr. Jack W. Lincoln (ASD/ENFS) were technical advisors for the program. Dr. Sherrell D. Manning of the General Dynamics' Structural Technology Staff was the Program Manager and co-investigator along with Dr. Jann N. Yang of United Analysis Incorporated.

The following reports (AFWAL-TR-86-3017) were also prepared under the "Advanced Durability Analysis" program:

- Volume I - Analytical Methods
- Volume II - Analytical Predictions, Test Results and Analytical Correlations
- Volume III - Fractographic Test Data
- Volume IV - Executive Summary
- Volume V - Durability Analysis Software User's Guide

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SECTION I

INTRODUCTION

The second edition of the Durability Design Handbook for metallic airframes has been updated to also cover functional impairment due to fuel leaks and ligament breakage. In the first edition [1] the durability analysis methods were limited to functional impairment due to excessive cracking in the small crack size region (e.g., cracks < 0.10"). The initial durability analysis method for the small crack size region has been extended to also cover large through-the-thickness cracks (e.g., 0.50" - 0.75") associated with fuel leaks and ligament breakage.

Objectives of the handbook are: (1) summarize and interpret the essential U. S. Air Force Durability Design requirements for metallic airframes, (2) provide durability analysis criteria for economic life and durability critical parts, (3) provide state-of-the-art durability analysis concepts and methods for determining the initial fatigue quality of clearance-fit fastener holes, the probability of crack exceedance at any service time and the cumulative distribution of service time to reach any specified crack size, (4) provide guidelines and design data for implementing the durability analysis method and for assisting contractor and USAF personnel in complying with the intent of the durability specifications for metallic airframes.

The methodology accounts for the initial fatigue quality variation of structural details, the crack growth accumulation for a population of structural details under specified design conditions and structural properties. Step-by-step procedures are provided.

The durability analysis approach [2-6] conceptually described in Fig. 1-1, reflects a probabilistic approach, a

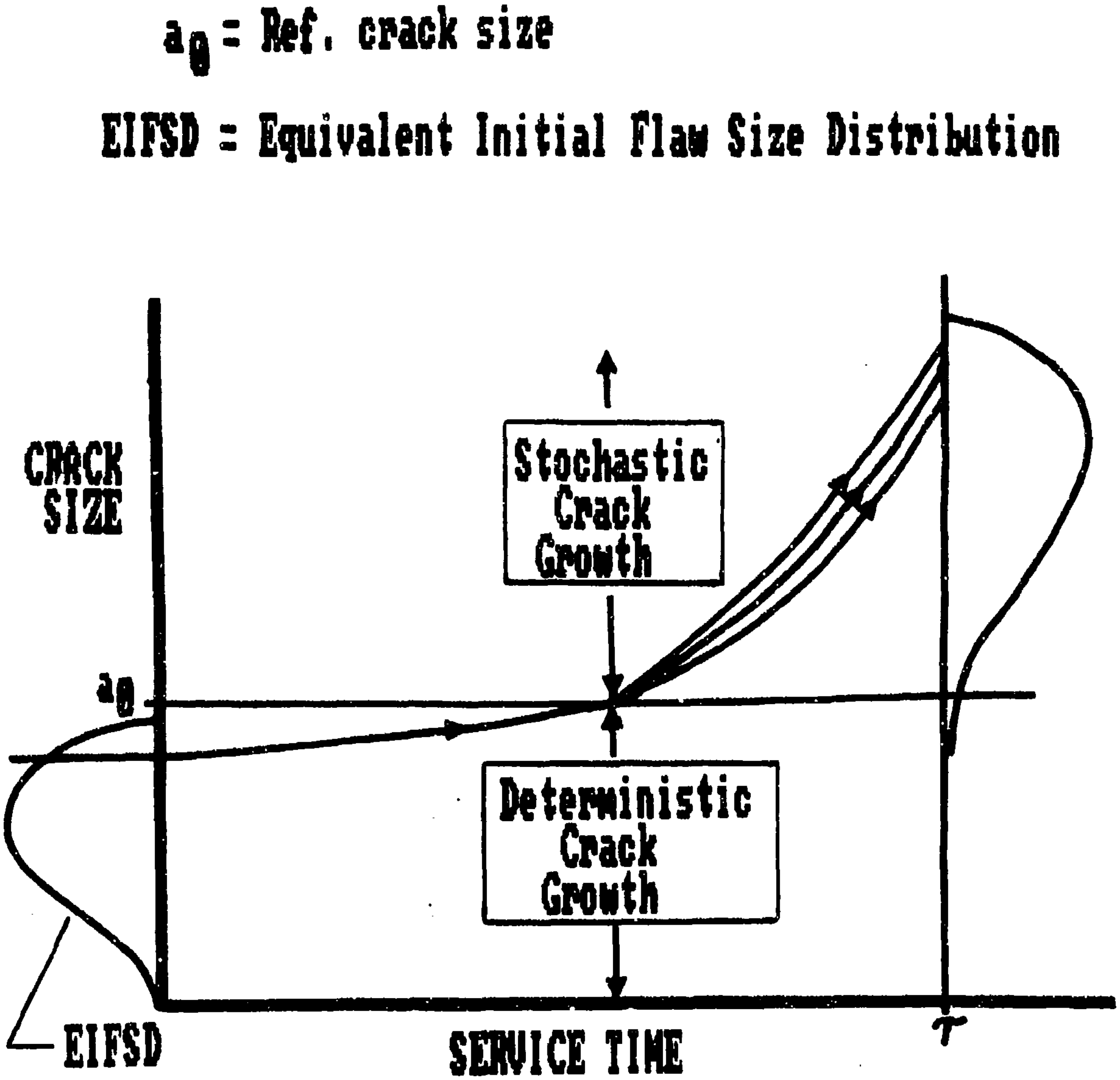


Figure 1-1. Durability Analysis Approach.

fracture mechanics philosophy and both deterministic and stochastic crack growth methods. It can be used to predict the probability of crack exceedance at any service time and/or the cumulative distribution of service time to reach any given crack size. The methodology applies to the small crack size range associated with excessive cracking (e.g., < 0.05") and to large through-the-thickness cracks (e.g., 0.50" - 0.75") associated with fuel leakage/ligament breakage.

No matter what form, location or combination the as-manufactured flaws may have in structural details (e.g., scratches, burrs, microscopic imperfections, etc.) or whatever the source of fatigue cracking may be, a practical method of representing the as-manufactured condition is needed for durability analysis. This is taken care of by the equivalent initial flaw size (EIFS) concept.

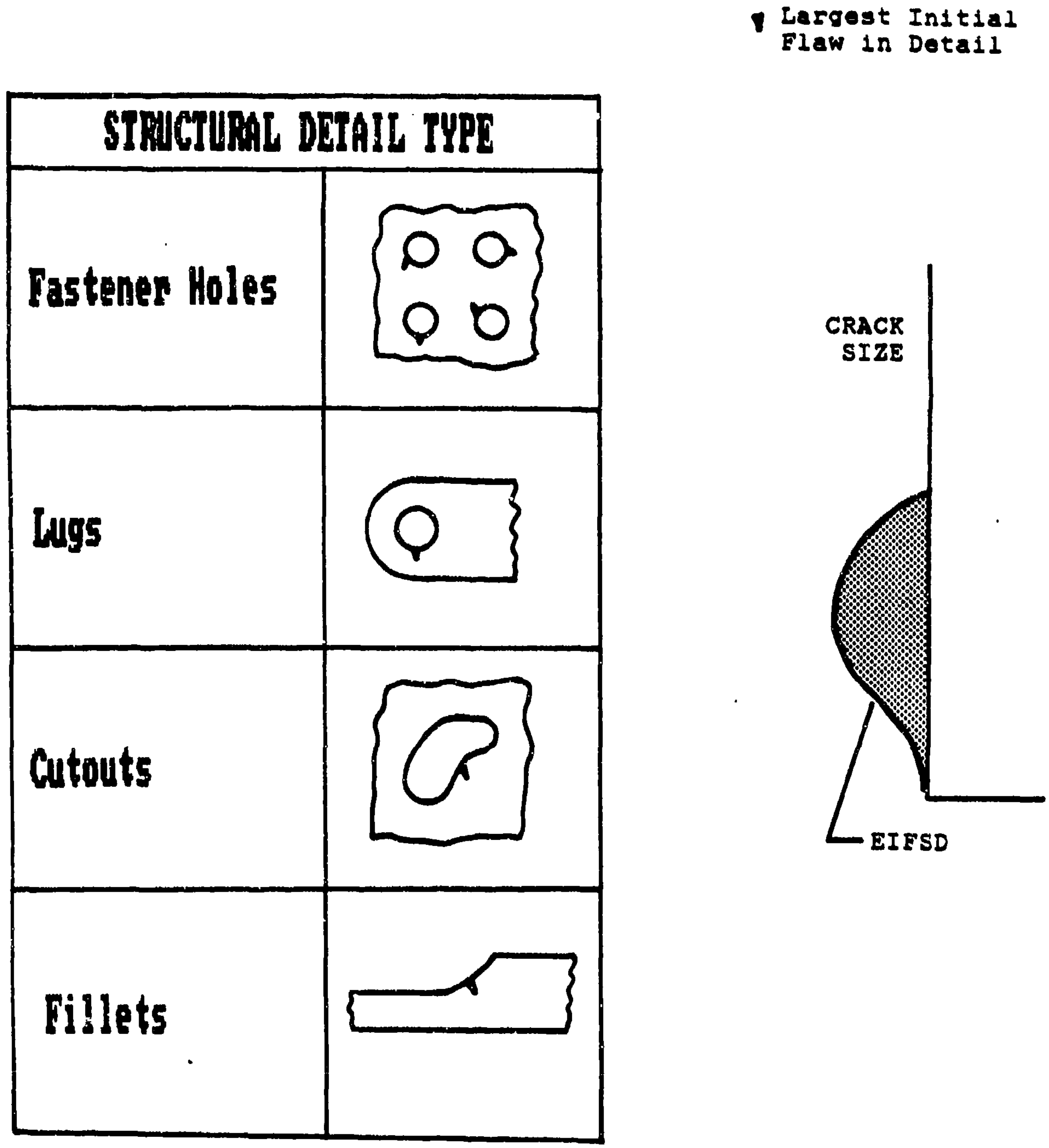
An equivalent initial flaw is an artificial crack size which results in an actual crack size at an actual point in time when the initial flaw is grown forward. It is determined by back-extrapolating fractographic results. It has the following characteristics: (1) An EIFS is an artificial crack assumed to represent the initial fatigue quality of a structural detail in the as-manufactured condition whatever the source of fatigue cracking may be, (2) it has no direct relationship to actual initial flaws in fastener holes such as scratches, burrs, microdefects, etc., and it cannot be verified by NDI, (3) it has a universal crack shape in which the crack size is measured in the direction of crack propagation, (4) EIFSs are in a fracture mechanics format but they are not subject to such laws or limitations as the "short crack effect," (5) it depends on the fractographic data used, the fractographic crack size range used for the back-extrapolation and the crack growth rate model used, (6) it must be grown forward in a manner consistent with the basis for the EIFS, and (7) EIFSs are not unique -- a different set is obtained for each crack growth law used for the back-extrapolation.

The initial fatigue quality (IFQ) of a structural detail (e.g., fastener holes, cutouts, fillets, lugs, etc.) is represented by an equivalent initial flaw size distribution (EIFSD). EIFS is treated as a random variable. A different EIFSD should be established for different types of structural details (e.g., see Fig. 1-2) reflected in the durability analysis.

The durability analysis can be used to estimate statistically the "extent of damage" (such as mean and extreme values in a durability-critical component) at any service time (e.g., see Fig. 1-3). The extent of damage can be described quantitatively by the number of structural details or ligaments expected to exceed specified crack size limits with given probability at any service time τ. Hence, the durability analysis provides a quantitative description of structural durability in physically meaningful terms.

Durability analysis procedures are summarized as follows: (1) define the equivalent initial flaw size distribution (EIFSD) using fractographic data in the small crack size region (e.g., 0.01" - 0.05"), (2) use fractographic data pooling procedure and statistical scaling technique to estimate the EIFSD parameters in a "global sense" for a "single hole population" basis, and (3) use the two-segment deterministic-stochastic crack growth approach (DCGA-SCGA) [2,3,6] to predict the extent of damage in the entire durability critical component; the two-segment deterministic crack growth approach (DCGA-DCGA) [2,3, 6,7] is also reasonable but it is slightly less conservative than the DCGA-SCGA.

Procedures have been developed for defining initial fa-



NOTES: (1) Largest initial flaw size in each structural detail is a random variable
(2) An EIFSD is required for each structural detail type

Figure 1-2. Initial Fatigue Quality for Each Detail Type is Represented by an Equivalent Initial Flaw Size Distribution (EIFSD).

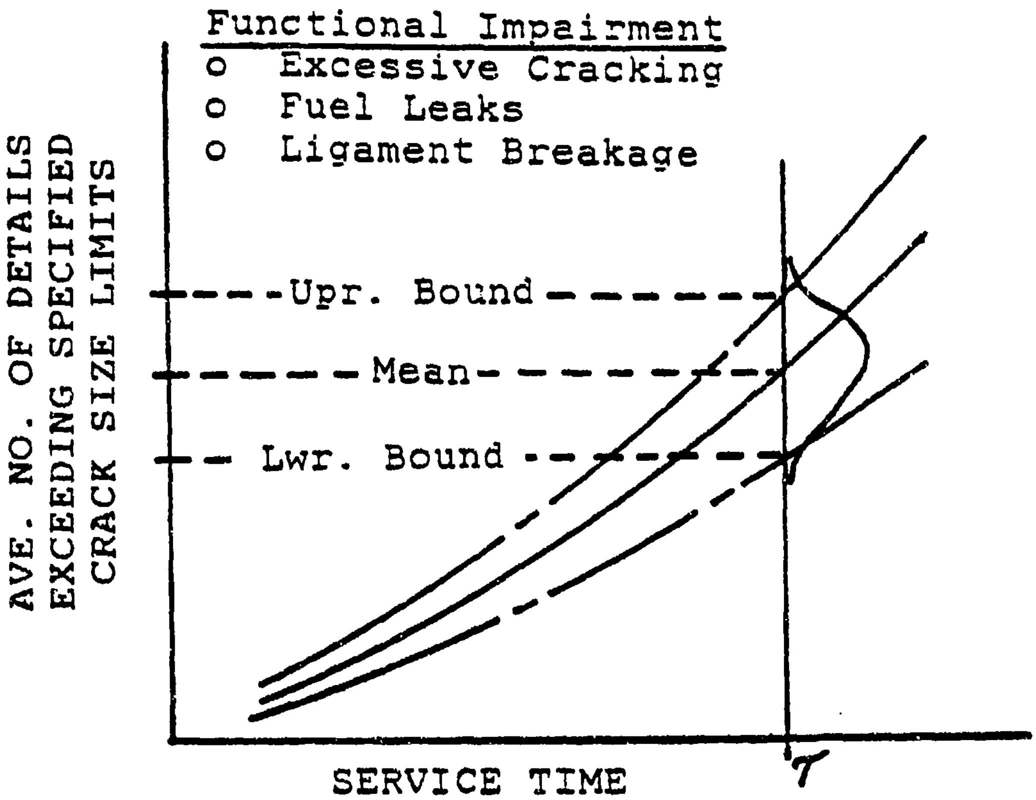


Figure 1-3. Extent of Damage Concept for Quantitative Durability Analysis.

tigue quality. These procedures could be used to standardize the way initial flaw sizes are determined from fractographic data. A better understanding of initial flaw sizes (i.e., what they are and limitations) has been developed [e.g., 2-4]. For consistent durability analysis predictions, equivalent initial flaws must be used in the same context for which they were defined. This means that equivalent initial flaws must be grown forward in the same manner the EIFSs were established by back-extrapolating fractographic results.

SECTION II

DURABILITY DESIGN REQUIREMENTS AND ANALYSIS CRITERIA/GUIDELINES

2.1 INTRODUCTION

The purpose of this section is to: (1) briefly review and interpret the important elements of the Air Force's durability design requirements [8-11], (2) discuss durability critical parts criteria, (3) provide guidelines and recommended formats for defining quantitative economic life criteria, and (4) discuss functional impairment due to fuel leaks and ligament breakage.

2.2 DURABILITY DESIGN REQUIREMENTS

2.2.1 Objective and Scope

The objective of the Air Force durability design requirements [8-11] is to minimize in-service maintenance costs and maximize operational readiness through proper selection of materials, stress levels, design details, inspections, and protection systems. These design requirements include both analyses and tests.

2.2.2 General Requirements

Essential durability requirements, conceptually described in Fig. 2-1, are as follows:

- The economic life of the airframe must exceed one design service life.
- No functional impairment (e.g., loss of stiffness, loss of control effectiveness, loss of cabin pres-

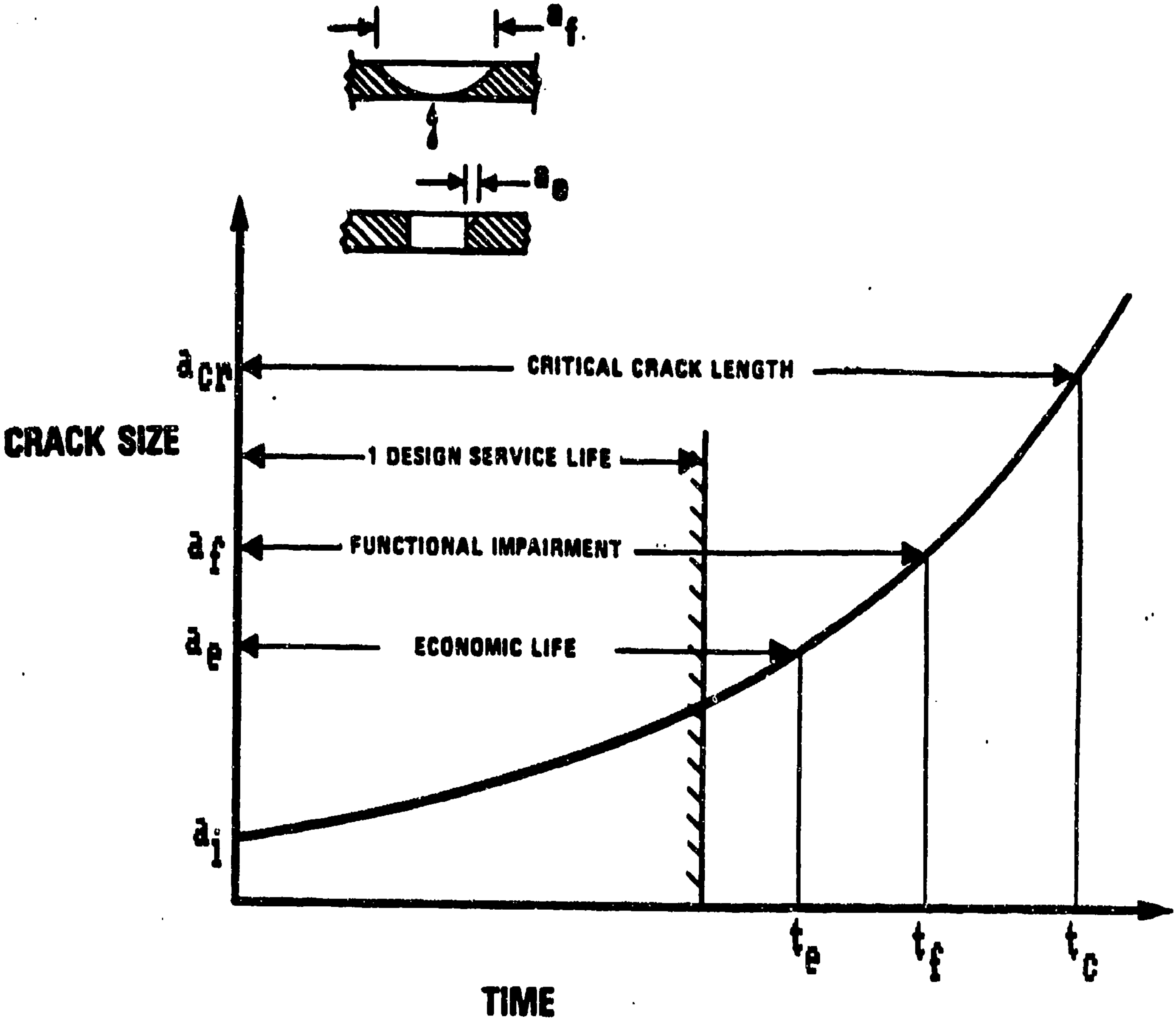


Figure 2-1. U. S. Air Force Durability Design Requirements.

sure or fuel leaks) shall occur in less than one design service life.

- The economic life of the airframe must be demonstrated analytically and experimentally.

2.2.3 Analytical Requirements

Analyses are required to demonstrate that the economic life of the airframe is greater than the design service life when subjected to the design service loads and design chemical/thermal environments. The economic life analysis must account for initial quality, environment, load sequence, material property variations, etc. The analysis must be verified by tests.

2.2.4 Experimental Requirements

Design development tests are required to provide an early evaluation of the durability of critical components and assemblies as well as the verification of the durability analysis.

A durability test of a full-scale airframe may also be required by the Air Force. The requirements for this test are:

1. The airframe must be durability tested to one lifetime. Critical structural areas must be inspected before the full production go-ahead decision.

2. Two lifetimes of durability testing plus an inspection of critical structural areas must be completed prior to delivery of the first production aircraft.

If the economic life of the airframe is not reached before two lifetimes of durability testing, the following options are available:

1. Terminate the durability testing and perform a nondestructive inspection followed by destructive teardown inspection.

2. Terminate the durability testing and perform damage tolerance testing and nondestructive inspection followed by a destructive teardown inspection.

3. Continue the durability testing for an approved period of time followed by either of the preceding options.

2.3 DURABILITY ANALYSIS CRITERIA

2.3.1 Durability Damage Modes

There are several modes of durability damage, including fatigue cracking, corrosion, wear, etc. Due to its importance and prevalence, fatigue cracking is the form of structural degradation considered in this handbook.

2.3.2 Durability Critical Parts Criteria

Criteria must be developed for determining which parts of an aircraft are durability critical (i.e., which parts must be designed to meet the durability design requirements). The durability critical parts criteria vary from aircraft to aircraft. They are especially dependent on the definition of economic life for the particular aircraft involved. A typical flow diagram for selecting which parts are durability critical is presented in Fig. 2-2. In Fig. 2-2, durability refers to the ability of an airframe to resist cracking whereas damage tolerance refers to the ability of an airframe

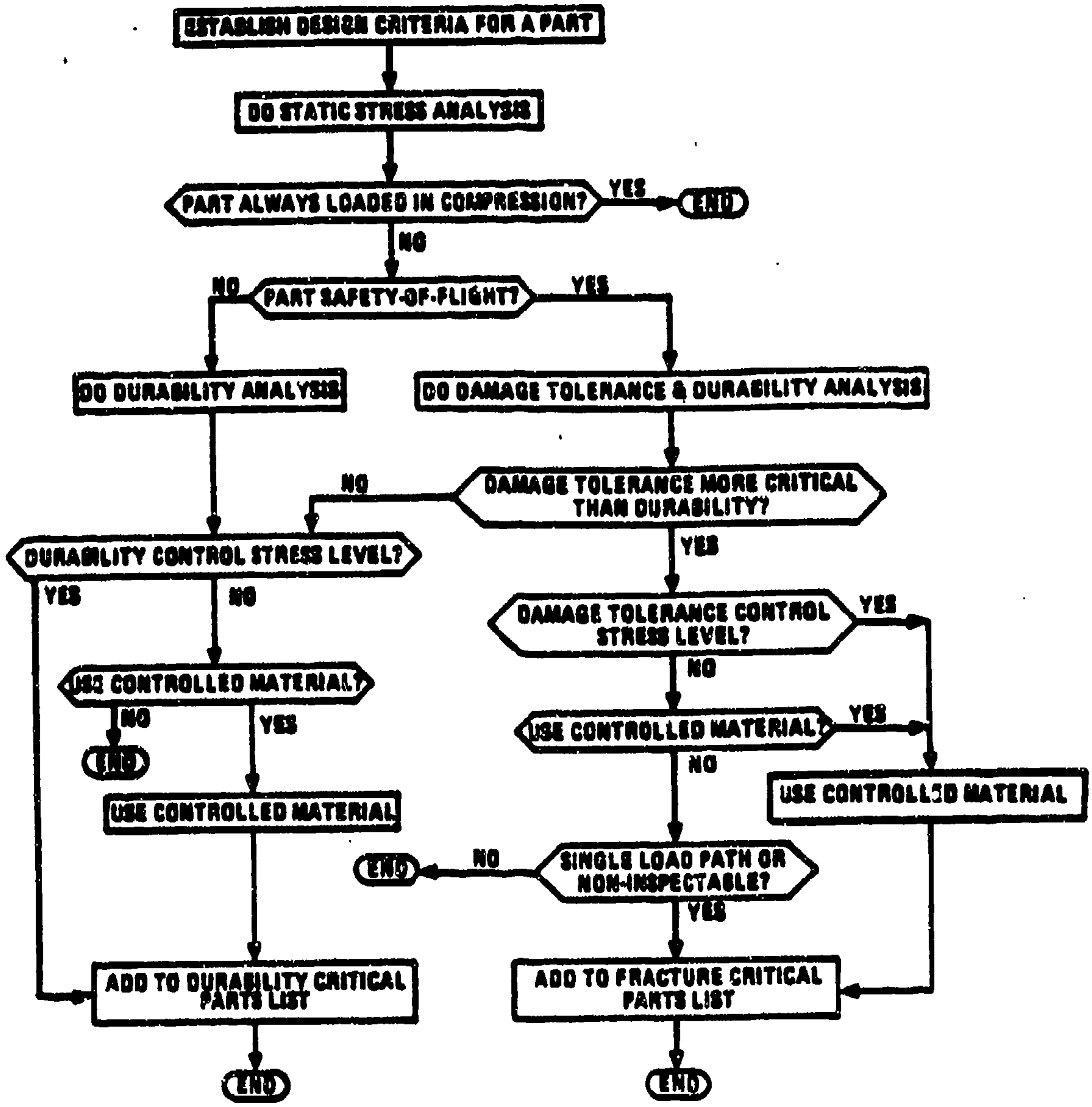


Figure 2-2. <u>Flow Diagram for Selecting Durability Critical Parts.</u>

to resist failure due to the presence of such cracks.

2.3.3 Economic Life Criteria/Guidalines

Criteria must be developed for determining the economic life of the particular aircraft of interest. Similar to the durability critical parts criteria, economic life criteria vary from aircraft to aircraft. They may be based on fastener hole repair (e.g., reaming the damaged fastener hole to the next nominal hole size), functional impairment (e.g., fuel leakage), residual strength, etc. Two promising analytical formats for quantifying the economical life of an airframe are (1) the probability of crack exceedance, and (2) cost ratio: repair cost/replacement cost. Both formats require a durability analysis methodology capable of quantifying the extent of aircraft structural damage as a function of service time. For example, assume the economic life criteria are based on the number of fastener holes which cannot be economically repaired (i.e., number of fastener holes with crack sizes equal to or greater than specified size x_1). Then an analytical format for quantifying economic life is presented in Fig. 2-3. In Fig. 2-3, P is the exceedance probability. Various aspects of economic life are discussed further in the following subsections and elsewhere [12-23].

2.3.3.1 <u>Economic Life Definition</u>

The economic life of an aircraft structure is currently defined in qualitative terms: "...the occurrence of widespread damage which is uneconomical to repair and, if not repaired, could cause functional problems affecting operational readiness" [8,10]. Acceptable limits for "widespread damage" and "uneconomical repairs" must be defined for each aircraft design and such limits must be approved by the Air Force.

A quantitative definition of economic life is not given

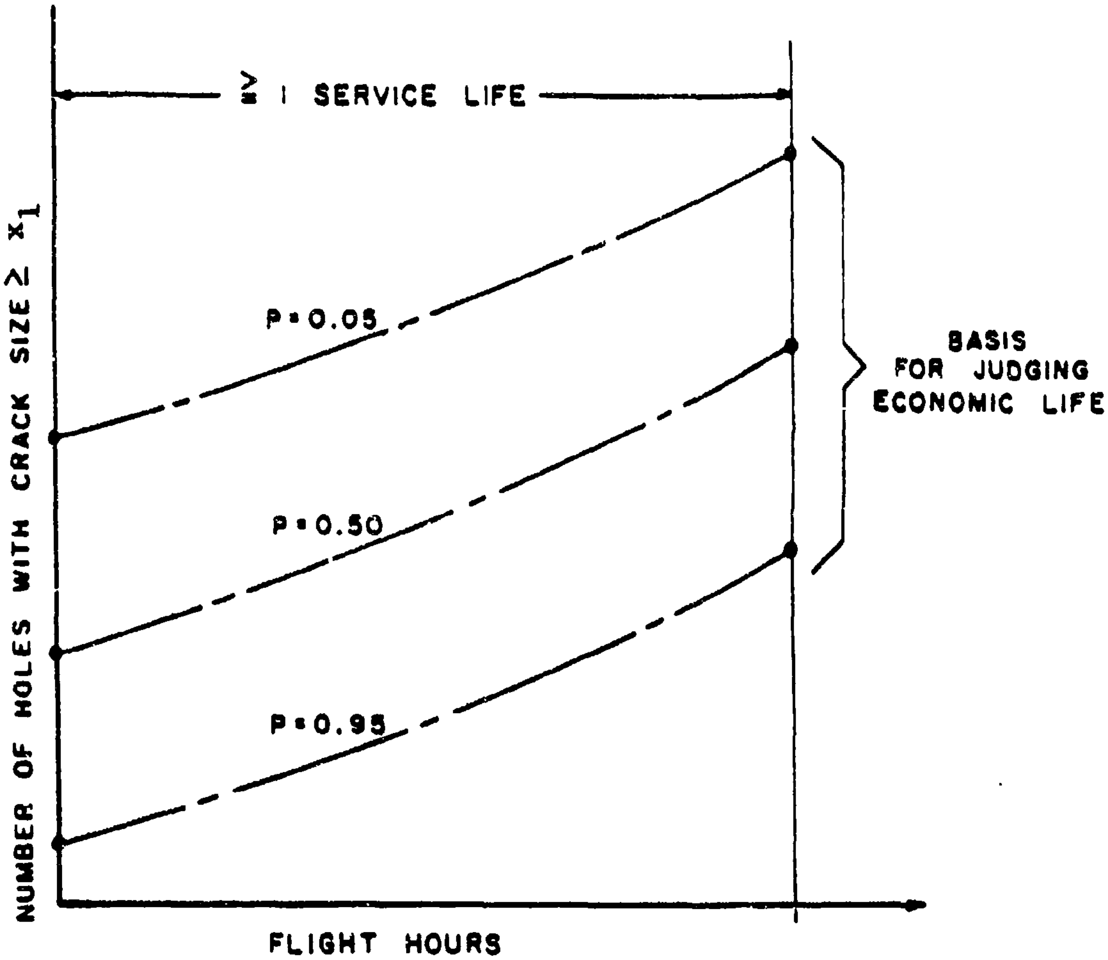


Figure 2-3. Analytical Format for Economic Life.

in this handbook. However, guidelines are presented for specifying economic life criterion (Ref. Section 2.3.3.4). In any case, quantitative criteria for the economic life of aircraft structures should be based on specific aircraft requirements and the user's acceptable limits for aircraft performance and maintenance costs.

2.3.3.2 Economic Repair Limit

The "economic repair limit" is the maximum crack size in a structural detail that can be economically repaired. Such limits can easily be defined from geometric considerations for fastener holes but such limits are more difficult to define for structural details such as cutouts, fillets, etc. For example, the economic repair limit for a fastener hole may be governed by the largest radial crack that can be cleaned up by reaming the hole to the next fastener size (e.g., 0.03" to 0.05" radial crack).

The objective of the durability analysis method presented in this handbook is to analytically predict the number of structural details with a crack size which would cause an uneconomical repair or functional impairment. The user must define the uneconomical repair or functional impairment crack size for the details to be included in the extent-of-damage assessment. Such crack sizes depend on considerations such as structural detail type, location, accessability, inspectability, repairability, repair costs, etc.

Structural details may contain one or more cracks. However, structural durability is concerned with the largest crack in each detail which may require repair or part replacement.

2.3.3.3 Extent of Damage

The extent of damage is a quantitative measure of the number of structural details containing cracks that exceed specified crack size limits as a function of service time. Structural maintenance requirements and costs depend on the number of structural details requiring repair. The "durability" of the structure depends on the extent of damage for the population of structural details in a part, a component, or airframe.

The statistics of the extent of damage, such as mean and extreme values for selected probabilities, can be predicted using the analytical tools provided in this handbook. Extent of damage predictions provide the basis for analytically ensuring that a durability-critical part or component will not crack excessively in less than one service life.

2.3.3.4 Formats for Economic Life Criteria

Two analytical formats for defining quantitative economic life criteria are recommended: (1) probability of crack exceedance, and (2) cost ratio: repair cost/replacement cost [15-18]. The analytical tools described in this handbook can be used to predict results in these formats. Various aspects of each format for a quantitative economic life criterion are discussed below, including examples and guidelines (Ref. Fig. 2-3).

2.3.3.4.1 Probability of Crack Exceedance. The probability that a crack will be larger than a specified crack size at a particular service time is referred to as the "probability of crack exceedance." This quantity is a fundamental output of the durability analysis methodology described in this handbook. For example, in Fig. 2-4 the probability of exceeding crack size x_1 at $t = \tau$ is represented by the cross-hatched area un-

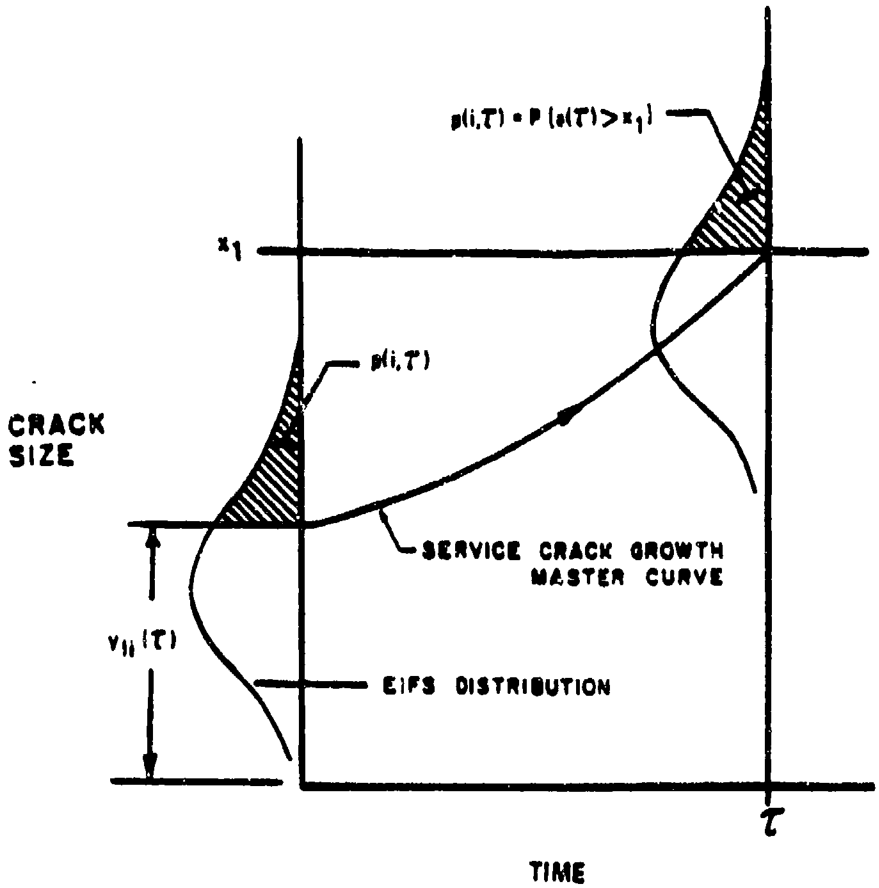


Figure 2-4. Probability of Crack Exceedance Concept.

der the crack size density function at $t = \tau$. When the deterministic crack growth approach is used, crack size rankings in the respective distributions for two different times are preserved; namely, the crack size x_1 at $t = \tau$ has the same rank (or percentile) as the initial crack size at $y_{1i}(\tau)$ at $t = 0$. The probability of crack exceedance can be used to predict the expected number of repairs in a given service interval [16,18]. It also provides a basis for judging airframe durability and for analytically demonstrating design compliance with the governing criterion for economic life.

Another explanation of the probability of crack exceedance concept will now be given. Each common structural detail, in a group of details having a common stress history, has a single dominant crack. Such cracks form a crack population and their "initial" size depends on the manufacturing quality for each structural detail. The probability of exceeding crack size x_1 at time τ is represented by the cross-hatched area under the probability density of crack sizes shown in Fig. 2-4. Suppose the probability of crack exceedance is $p(i,\tau) = 0.05$. This means that on the average 5% of the details (e.g., 5% of the fastener holes) in a part or component would be expected to have a crack size $\geq x_1$ at time τ. $p(i,\tau)$ is a fundamental measure of the extent of damage. Using the binomial distribution, the extent of damage for different groups of details can be combined to quantify the overall damage for a part, a component or airframe.

The allowable crack exceedance is one criterion recommended for quantifying economic life. Although this handbook provides guidelines for quantifying the allowable crack exceedance, specific values are not presented for demonstrating design compliance with the Air Force's durability design requirements. Such values must be tailored for specific aircraft structure and the user's acceptable limit for structural maintenance requirements/costs, functional impairment, operational readiness, etc. The allowable crack exceedance criterion for economic life design compliance shall be approved by the Air Force.

The allowable crack exceedance for a part or component depends on several factors, including: criticality, accessability, inspectability, repairability, cost, operational readiness, acceptable risk limits, etc. For example, an expensive fracture critical part may be embedded into the wing under-structure. The part is not readily accessible and it is difficult to inspect and repair. Suppose the bolt hole for this part governs its economic life. Then a lower allowable crack exceedance may be desired than for an equally critical part that is more accessible and inspectable. For example, an average of 2% crack exceedance at 1.2 service lives might be suitable in the first case and an average of 5% might be appropriate for different circumstances.

An example for the probability of crack exceedance criterion is as follows. The economic life of a part or component is reached when 5 percent of the structural details (e.g., fastener holes, cutouts, fillets, etc.) have reached a crack size $\geq$ a specified limiting crack size at 1.2 service lives. The limiting crack size depends on the type of structural detail, the economic repair limit, and the crack size which would cause functional impairment (limiting case). Structural safety or damage tolerance must not be compromised. Also, the specified limiting crack size for each detail type should account for inspection capabilities and requirements, and operational readiness.

The economic life criterion described (i.e., 5% crack exceedance) can be used to demonstrate economic life design compliance analytically and experimentally. The analytical tools presented in this handbook can be used to quantify the extent of damage in terms of crack exceedance. Therefore, given the criterion for economic life, design compliance can be analytically assured. Experimental compliance can be determined based on the results of the durability demonstration test results.

2.3.3.4.2 Repair Cost/Replacement Cost Ratio. The ratio of repair cost/replacement cost is another recommended criterion for quantitative economic life. For example, when the cost to repair a part or component exceeds the cost to replace it, the economic life is reached. In other words, the economic life is reached when the cost ratio = 1 at a specified service life (e.g., 1.2 service lives).

Input from the aircraft user is needed to define acceptable allowable cost ratios for different parts or components. Allowable cost ratios could be specified for particular design situations and user's goals.

Repair costs are proportional to the number of structural details (e.g., fastener holes) requiring repair after a specified service time. The analytical tools described in this handbook can be used to quantify the number of details requiring repair as a function of service time. Although specific repair cost data may be difficult to obtain for different circumstances and replacement costs may vary, the cost ratio can be estimated using assumed repair and replacement costs.

The cost ratio criterion for economic life is not recommended for demonstrating design compliance unless acceptable cost data are available. However, this criterion is recommended for evaluating user design tradeoff options affecting the life-cycle-cost of the airframe. The analytical tools described in this handbook can be used to evaluate the life-cycle-cost design tradeoffs.

2.4 FUNCTIONAL IMPAIRMENT DUE TO FUEL LEAKS/LIGAMENT BREAKAGE

Fuel leaks and ligament breakage are other forms of functional impairment which must be accounted for in the design of metallic airframes. Large through-the-thickness cracks may cause fuel leaks with a progressive increase in the state of damage as a function of service time. Such cracks may not pose an immediate structural safety problem. However, they may affect the operational readiness of the aircraft and increase the structural maintenance requirements and repair costs. Without inspection, repair and maintenance the damaged areas may eventually lead to a safety of flight problem or necessitate expensive repairs.

Fuel leaks are a fire hazard. They increase fuel consumption and may affect the operational readiness of the aircraft. Ligament breakage is like a cancer in that damage may continue to spread with increased service time. For example, a crack in one hole may grow to an adjacent hole and may continue to grow in service to other holes. An adjacent hole may act as a crack stopper but the redistribution or shedding of load around the damaged area under service conditions may eventually spread the damage to adjacent areas.

The durability analysis tools in this handbook can be used to assess the probability of functional impairment due to excessive cracking, fuel leaks or ligament breakage. Such tools can be used during the design stage to select materials, design concepts and allowable stress levels to satisfy the Air Force's durability design requirements.

SECTION III

SUMMARY OF THE DURABILITY ANALYSIS METHOD

Essential elements and equations of the durability analysis method are summarized in this section. The technical approach, based on the two-segment DCGA-SCGA, is presented, including step-by-step procedures for implementing the method. Durability analysis guidelines are given in Section IV and the methods are demonstrated in Section V. Further details are given elsewhere [2-7,24-29].

3.1 GENERAL DESCRIPTION OF THE TECHNICAL APPROACH

The initial fatigue quality (IFQ) of structural details reflected in the durability analysis is represented by an equivalent initial flaw size distribution (EIFSD). An EIFSD is defined by structural detail types (e.g., see Fig. 1-2). An equivalent initial flaw size (EIFS) is an artificial crack size at time zero which results in an actual crack size when the EIFS is grown forward. EIFSs are determined by back-extrapolating fractographic results to time zero. An EIFS has no direct relationship to actual initial flaws (e.g., scratches, burrs, microdefects, etc.) in a structural detail and such flaws cannot be verified by NDI. An EIFS is assumed to be a random variable which is statistically described by an EIFSD.

Once a suitable EIFSD has been determined, the EIFSD is grown forward using a two-segment deterministic-stochastic crack growth rate model. The probability of crack exceedance, $p(i,\tau)$, at any service time τ and/or the cumulative distribution of service time to reach any specified crack size x_1, $F_{T(x_1)}(\tau)$, can be predicted for a durability-critical component. Using the probability of crack exceedance predictions, the assumption of statistically independent cracking and the binomial distribution, the extent of damage mean ($P = 0.5$) and upper bound limit (e.g., $P = 0.05$) can be estimated for selected exceedance probabilities P. The extent of damage defines statistically the number of structural details or ligaments in a durability-critical component expected to exceed crack size limits for functional impairment at a given service time. Hence, the extent of damage provides a basis for incorporating durability requirements into the design process and for evaluating durability design tradeoffs (e.g., material, design concept, stress level, load spectra, % bolt load transfer, etc.).

The technical approach for the durability analysis includes four essential steps: (1) determine the initial fatigue quality or EIFSD suitable for the structural details to be reflected in the durability analysis, (2) determine a suitable service crack growth master curve in two crack growth segments, (3) predict the probability of crack exceedance $p(i,\tau)$, at a given service time, and/or the cumulative distribution of service time to reach a given crack size x_1, and (4) estimate the extent of damage mean ($P = 0.5$) and upper bound limit for selected exceedance probability (e.g., $P = 0.05$) at any given service time.

Essential elements and features of the durability analysis method are conceptually described in Figs. 3-1 through 3-5. Details are given in the following and elsewhere [2-7, 24-29].

The durability analysis method, based on the two-segment DCGA-SCGA, has been demonstrated for clearance-fit fastener holes in 7475-T7351 aluminum for both protruding head and countersunk fasteners. The method has been demonstrated for both small (e.g., < 0.05") and large through-the-thickness (e.g., 0.5" - 0.75") fatigue cracks. The durability analysis method presented needs to be further investigated for other structural details (e.g., lugs, cutouts, fillets, etc.) and

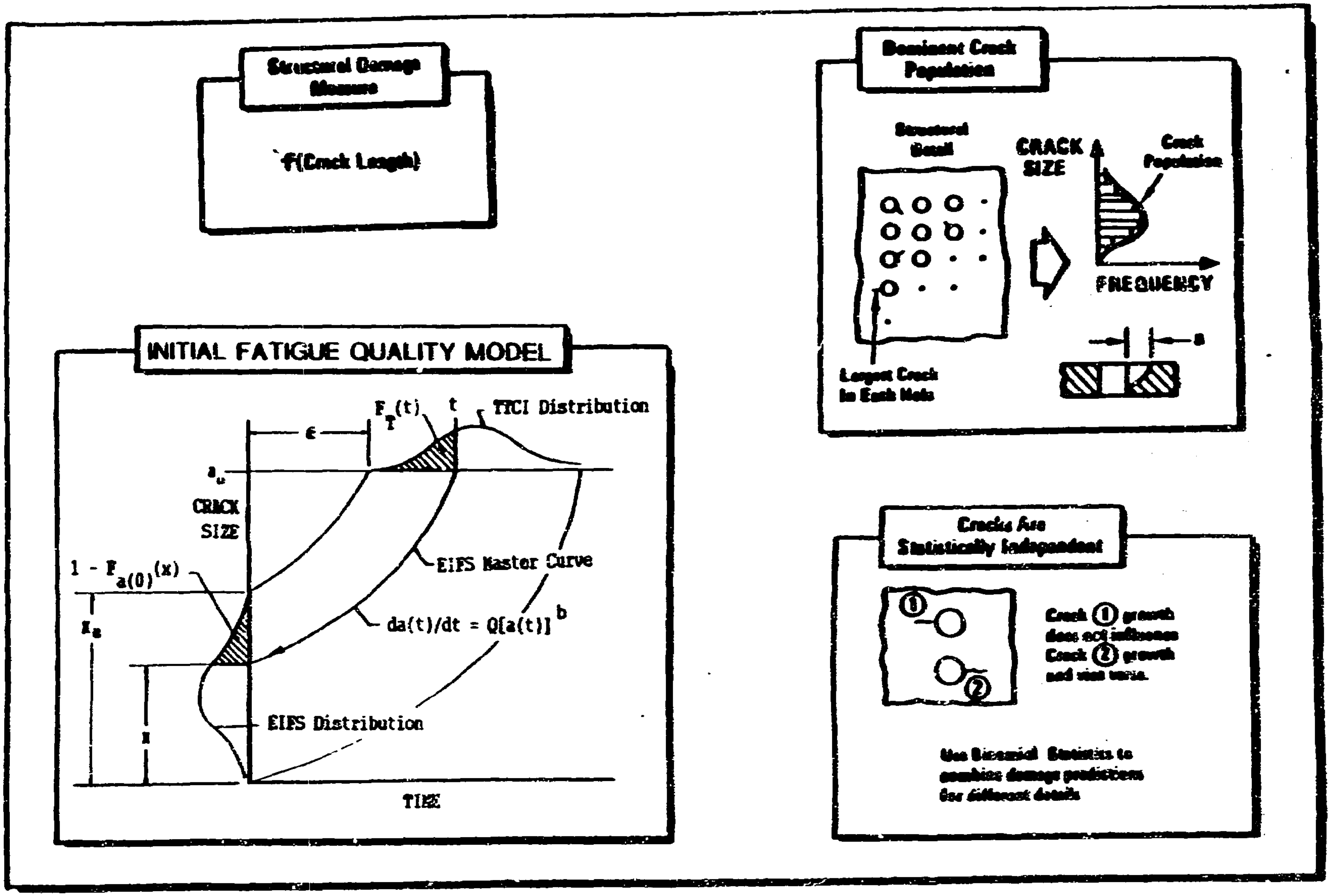


Figure 3-1. Elements of the Durability Analysis Methodology.

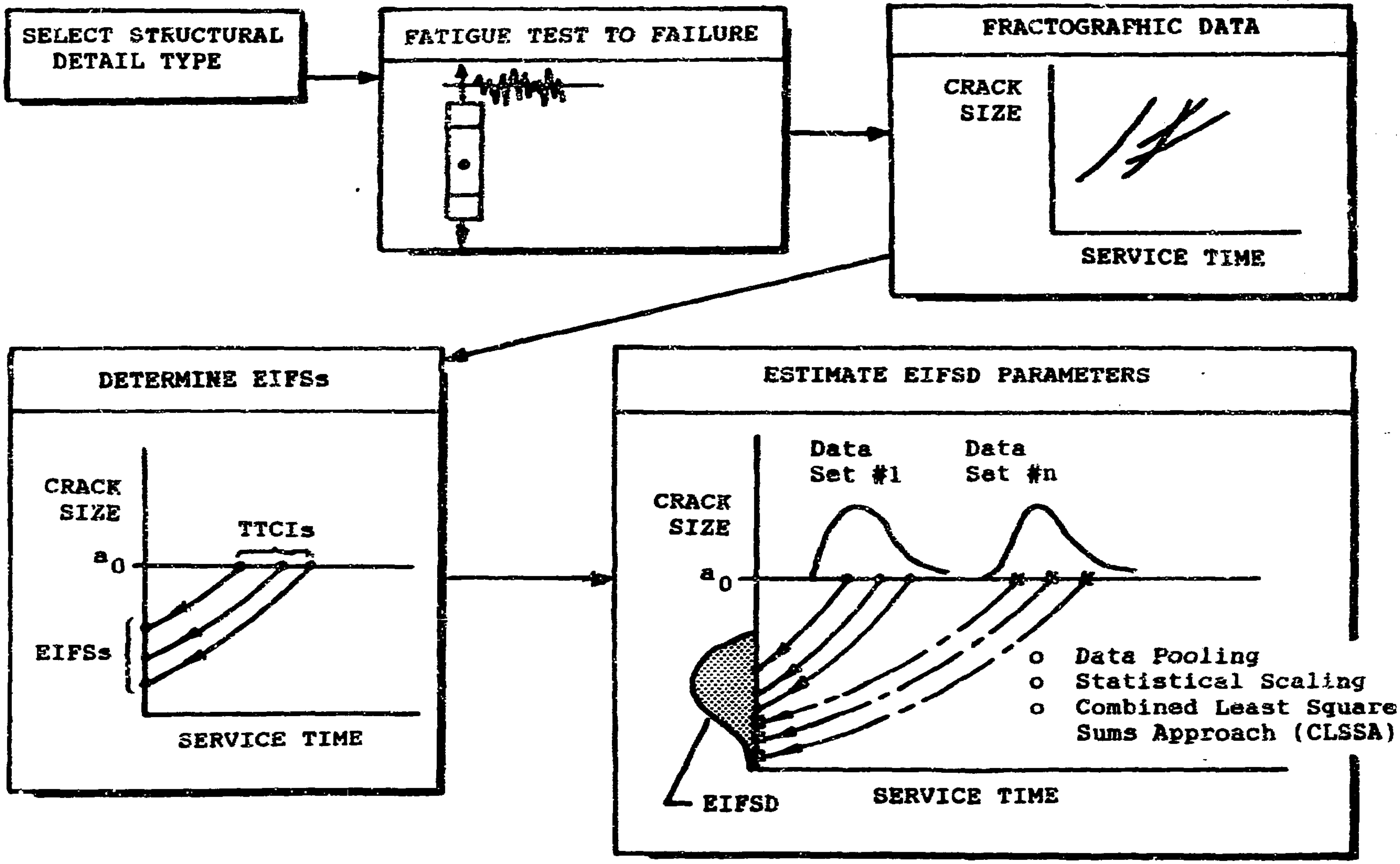
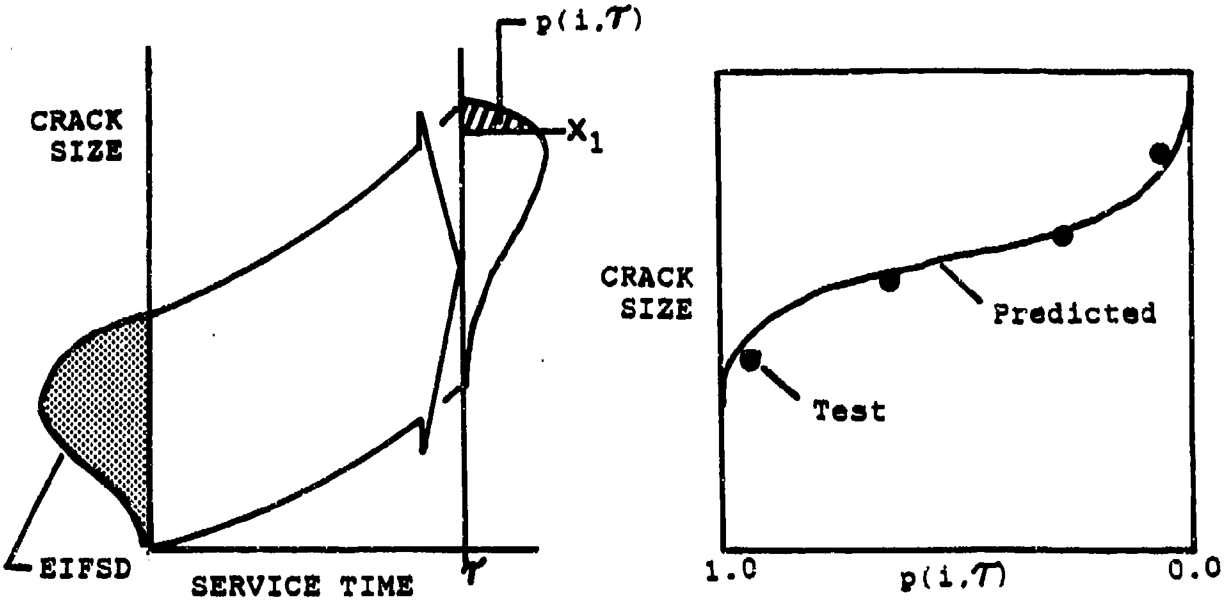
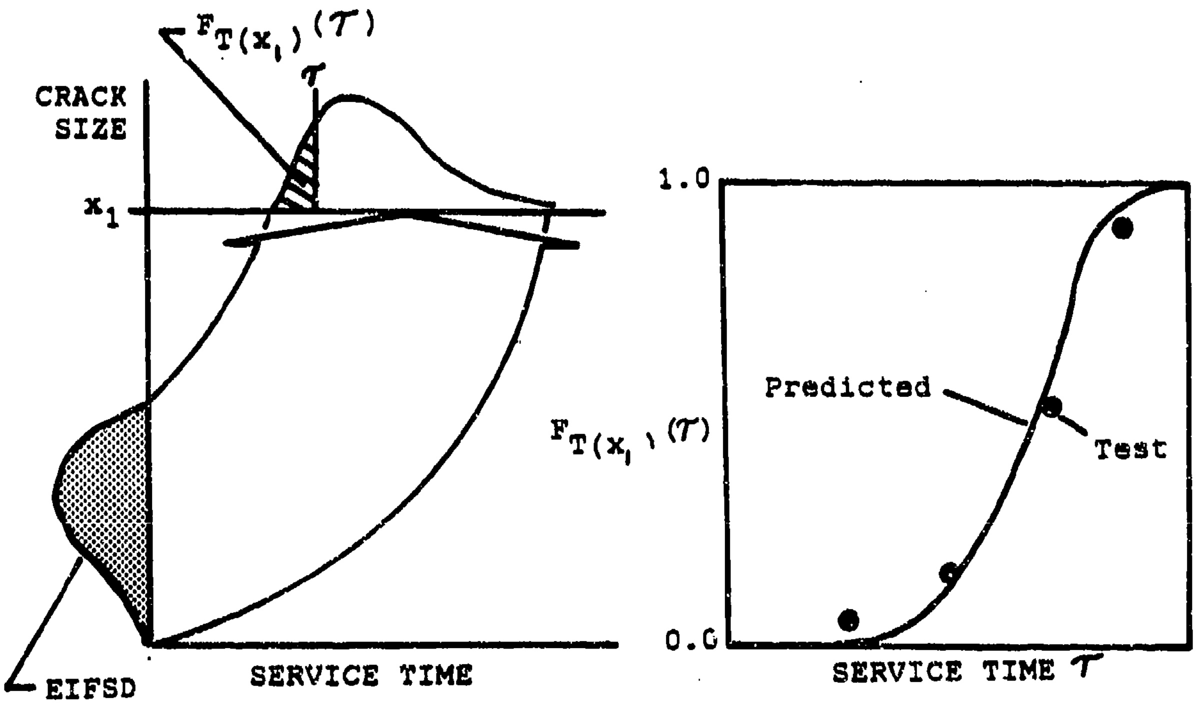


Figure 3-2. Essential Elements for Representing the Initial Fatigue Quality or EIFSD for Structural Details.



(a) Probability of Crack Exceedance at Service Time τ



(b) Cumulative Distribution of Service Time at Crack Size x_1.

Figure 3-3. Goodness-Of-Fit Plots for Justifying an EIFSD for Durability Analysis.

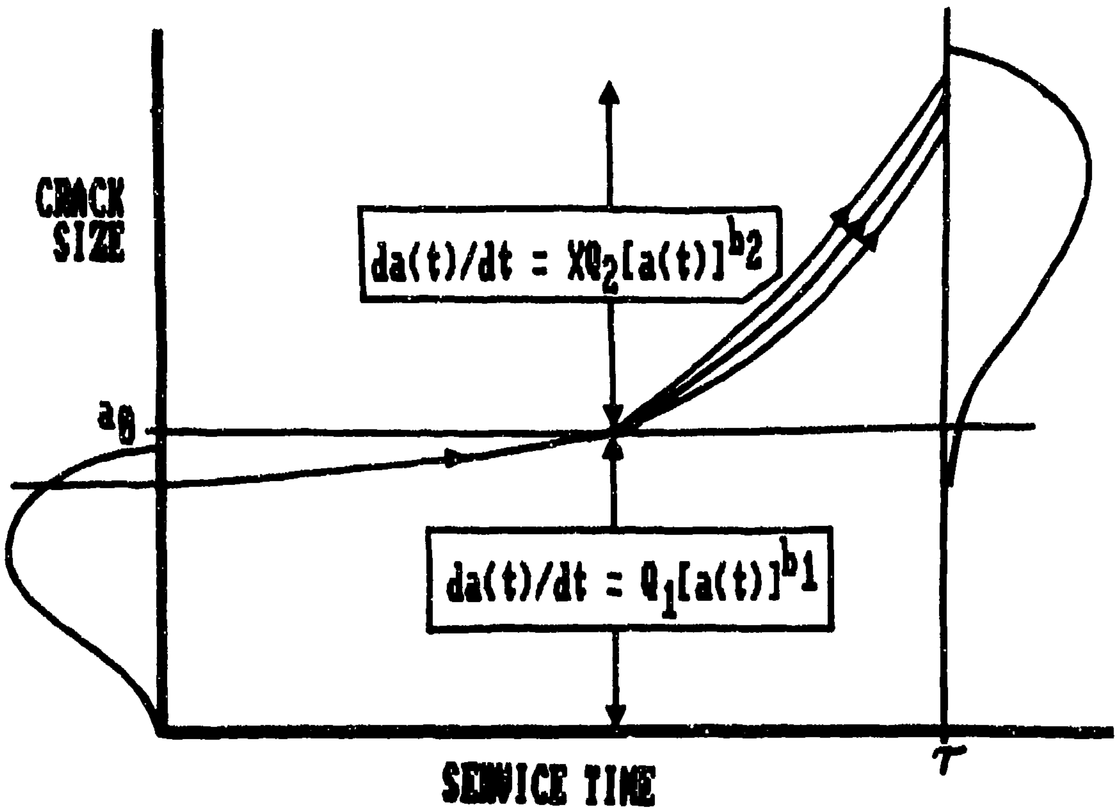


Figure 3-4. Two-Segment DCGA-SCGA for Durability Analysis.

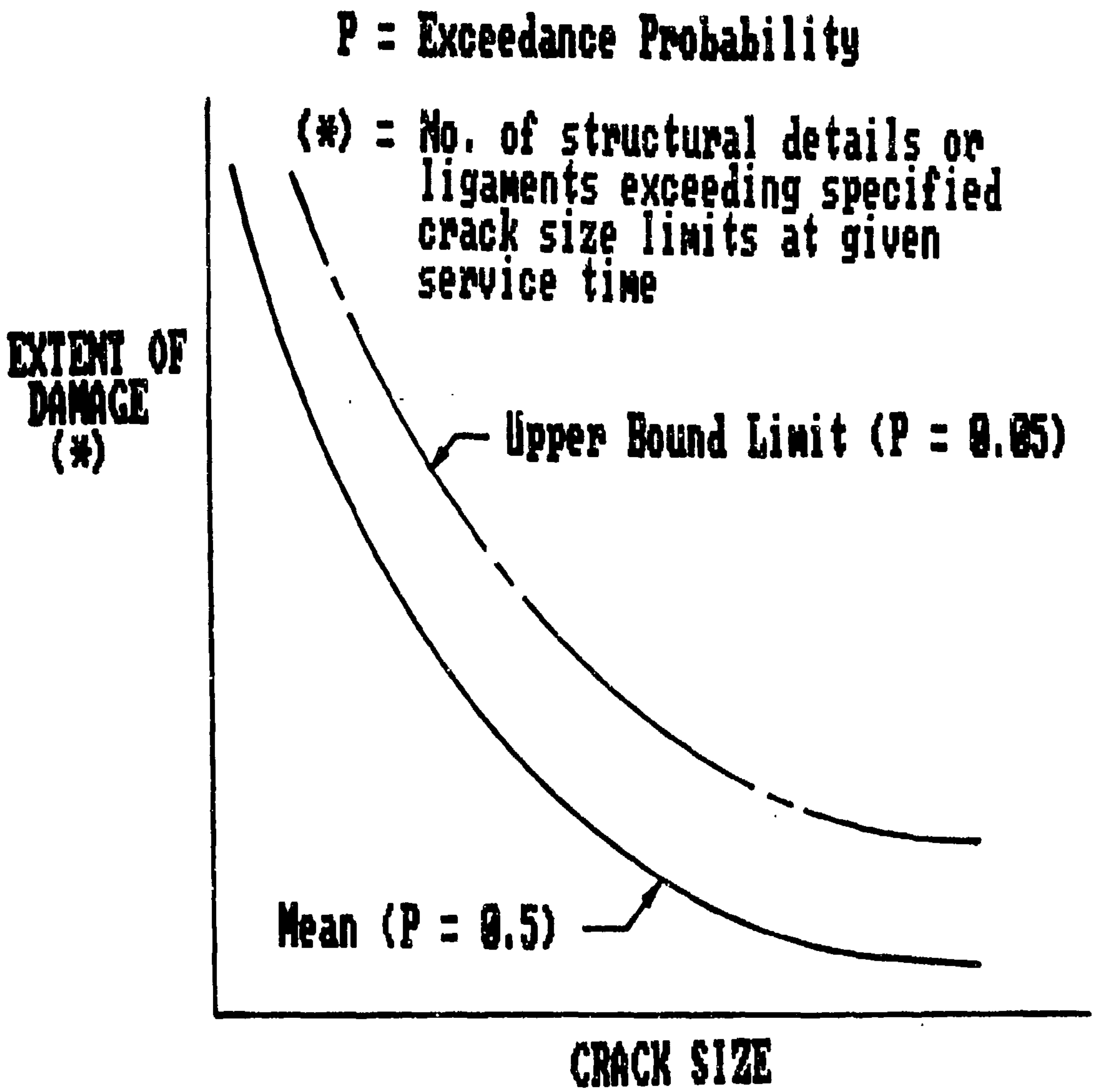


Figure 3-5. Extent of Damage Mean and Upper Bound Limit Concept.

for fastener holes with fatigue life enhancement such as interference fit fasteners, cold-working, etc. In any case, a general method and basic framework for performing "quantitative" durability analysis has been established.

3.2 INITIAL FATIGUE QUALITY

The initial fatigue quality (IFQ) defines the initially manufactured state of a structural detail or details with respect to initial flaws in a part, component, or airframe prior to service. The IFQ for a group of replicate details (e.g., fastener holes) is represented by an equivalent initial flaw size (EIFS) distribution.

The Weibull compatible distribution function proposed by Yang and Manning [16,30] has been found to be reasonable for representing the EIFS cumulative distribution [1,15-22,25-30]

$$F_{a(0)}(x) = \exp\left\{-\left[\frac{\ln(x_u/x)}{\phi}\right]^{\alpha}\right\} ; \quad 0 \leq x \leq x_u \qquad (3\text{-}1)$$

$$= 1.0 \qquad ; \quad x > x_u$$

in which x_u = EIFS upper bound limit; α and ϕ are empirical parameters.

An EIFS value for a fastener hole is determined by back-extrapolating fractographic data in a selected crack size range (AL-AU) using a simple but versatile deterministic crack growth rate model recommended by Yang and Manning [16, 30],

$$da(t)/dt = Q[a(t)]^{b} \qquad (3\text{-}2)$$

where $da(t)/dt$ = crack growth rate, $a(t)$ = crack size at any time t in flight hours, and Q and b are empirical crack growth rate parameters. The special case b = 1 is used herein.

After EIFS values, $a(0)$, are obtained from all available fractographic data, they are fitted by Eq. (3-1) to determine the EIFS distribution (EIFSD) parameters x_u, α, and ϕ. To predict the extent of cracking in service, the equivalent initial flaw size distribution is grown forward, and the distribution of the crack size $a(t)$ at any service time t can be derived from that of $a(0)$ given by Eq. (3-1). The EIFSD is grown forward to predict: (1) the probability that a crack in the ith stress region at any service time, τ, will exceed any given crack size, x_1, denoted by $p(i,\tau)$, and (2) the cumulative distribution of service time, $F_{T(x_1)}(\tau)$, for a crack in the ith stress region to reach any given crack size x_1. $p(i,\tau)$ is referred to as the crack exceedance probability. The two-segment deterministic-stochastic crack growth approach (DCGA-SCGA) is described in Section 3.4 and in Fig. 3-4 for growing the EIFSD forward to predict $p(i,\tau)$ and/or $F_{T(x_1)}(\tau)$.

3.3 ESTIMATION AND OPTIMIZATION OF EIFSD PARAMETERS

The essential procedures, concepts, and equations for estimating and optimizing EIFSD parameters x_u, α and ϕ in Eq. 3-1 are given in the following. Details are given elsewhere [2,3]. Six major topics are covered: (1) general procedure, (2) determination of EIFSs, (3) data pooling, (4) statistical scaling technique, (5) combined least square sums approach (CLSSA) and (6) optimization of parameters and goodness-of--fit.

3.3.1 General Procedure

1. Select fractographic data set(s) to be used to determine the EIFSD. The data sets should be for the same material, same type load spectrum (e.g., fighter, bomber or transport) and type fastener/hole/fit (i.e., straight bore or

countersunk).

2. Screen each fractographic data set for "anomalies" using software filename = "SCREEN" from Volume V [24]. Censor out fatigue cracks with anomalous behavior (e.g., surface crack rather than crack in bore of hole, cracks with crack growth rate extremes (i.e., very fast or very slow compared to rest of data, etc.).

3. Select a suitable fractographic crack size range, AL-AU (e.g., .01"-.05"), and a reference crack size, x_1, for defining service times or time-to-crack initiation (TTCI).

4. Estimate the EIFSs for each screened data set as described in Section 3.3.2. Use the largest fatigue crack in each specimen to determine the EIFSs.

5. Assume the EIFSD is represented by the Weibull compatible distribution function given in Eq. (3-1). Other EIFSD functions could also be used if appropriate (e.g., lognormal compatible [2], lognormal, two parameter Weibull, etc.). For a given EIFS upper bound limit, x_u (e.g., largest EIFS in data set(s) $\leq x_u \leq 0.05$") estimate the EIFSD parameters α and ϕ in Eq. (3-1) using: (1) the EIFSs from Step 4, (2) data pooling (Section 3.3.3), (3) statistical scaling (Section 3.3.4), and (4) combined least square sums approach (CLSSA) and an "EIFS fit" (Section 3.3.5).

6. Optimize the EIFSD parameters using the iterative procedure described in Section 3.3.6. For clearance-fit fastener holes and the Weibull compatible distribution function, an EIFS upper bound limit range of x_u = 0.02"-0.05" is reasonable.

7. Justify the candidate EIFSD for durability analysis by checking goodness-of-fit (see Fig. 3-3). Correlate theo-

retical predictions for the cumulative distribution of service time to reach the crack size x_1, $F_{T(x_1)}(\tau)$, and/or the cumulative distribution of crack size at service time τ, $F_{a(\tau)}(x)$, with fractographic results for selected data sets. Check goodness-of-fit using those fractographic data sets that were used to estimate the EIFSD. Where possible, other fractographic data sets should also be used to check the "goodness-of-fit."

Computer software, briefly described in Section VI, is available in Volume V [24] to estimate, optimize and justify the EIFSD parameters for durability analysis, including a goodness-of-fit plotting capability. This software can be implemented on an IBM or IBM-compatible personal computer.

3.3.2 Determination of EIFSs

Equivalent initial flaw sizes (EIFSs) for a given fractographic data set are determined by back-extrapolating fractographic results. The EIFS master curve for each fractographic data set is defined by integrating Eq. (3-2) (with b=1) from a(0) to a(t) to obtain

$$a(t) = a(0)\exp(Qt) \qquad (3\text{-}3)$$

or

$$\text{EIFS} = a(0) = a(t)\exp(-Qt) \qquad (3\text{-}4)$$

in which Q = empirical crack growth rate parameter (referred to as "pooled Q" for a data set), a(t) = crack size at any time t, a(0) = EIFS = crack size at t=0.

The "pooled "Q" value in Eq. (3-3) or (3-4) for a data set can be determined as follows. Suppose the ith fractographic data set contains a total of m fatigue cracks, where each fatigue crack is denoted by $j = 1, 2, \ldots, m$. The jth fatigue crack has a total of N pairs of fractographic data in the AL-AU range, denoted by $[a_j(t_k); t_k]$, i.e., $a_j(t_k)$ = kth crack size for the jth fatigue crack at service time t_k in the AL-AU range, where $k = 1, 2, \ldots, N$.

The crack growth rate parameter for a single fatigue crack, say the jth fatigue crack, denoted by Q_j, is estimated from fractographic data of the jth fatigue crack in the AL-AU range using Eq. (3-3) and the least squares fit procedure as follows

$$Q_j = \frac{N\sum_{k=1}^{N} X_k Y_k - \sum_{k=1}^{N} X_k \sum_{k=1}^{N} Y_k}{N\sum_{k=1}^{N} X_k^2 - \left(\sum_{k=1}^{N} X_k\right)^2} \qquad (3\text{-}5)$$

in which $X_k = t_k$ and $Y_k = \ln a_j(t_k)$.

Q_j given in Eq. (3-5) is the crack growth rate parameter for the jth crack and it is obtained using the fractographic data of the jth crack. Let Q_i be the crack growth rate parameter for the ith data set consisting of m cracks. Then, Q_i is referred to as the "pooled Q" value for the ith data set. It is obtained using all the fractographic data in the ith data set, i.e., all fractographic data for m cracks in the AL-AU range, and the least squares fit procedure,

$$Q_i = \exp\left[\frac{1}{m}\sum_{j=1}^{m} \ln Q_j\right] \qquad (3\text{-}6)$$

Once Q_i has been determined, the EIFSs for the ith data set can be determined as follows. Select a reference crack size x_1 within the AL-AU range (i.e., $AL \leq a_0 \leq AU$) for the time-to-crack-initiation. Then, determine for each fatigue crack in the data set, by interpolation or extrapolation, the time-to-crack-initiation (TTCI) and the results are denoted by $(T_1, T_2, \ldots, T_m)$.

The EIFS sample value for the jth crack, denoted by $a_j(0)$, is obtained from Eq. (3-4) by setting $t = T_j$ and $a(t) = a(T_j) = a_0$, i.e.,

$$a_j(0) = \text{jth EIFS} = a_0 \exp(-Q_i T_j); \; j = 1, 2, \ldots, m \qquad (3-7)$$

In other words, the jth crack with an EIFS, $a_j(0)$, will grow to the reference crack size a_0 at T_j. Equation (3-7) can also be interpreted in another form; i.e., the reference crack size a_0 at T_j is back-extrapolated to time zero to determine the corresponding EIFS value, $a_j(0)$.

Note that all EIFS values for the ith data set, i.e., $[a_1(0), a_2(0), \ldots, a_m(0)]$, are computed from Eq. (3-7) using the same Q_i value; i.e., the "pooled Q" value for the ith data set. The EIFS values thus obtained are referred to as "deterministic-based EIFSs" [2,3,6,7,27,29]. When the jth EIFS value for the jth crack is computed using its own crack growth rate parameter Q_j, Eq. (3-5), the EIFS data set thus established is referred to as the "stochastic-based EIFS" [2,3, 5,25,27]. As a result of extensive investigations conducted [2,3,5-7,25,27,29,59], the deterministic-based EIFS has been recommended.

Finally, given the crack growth rate parameter Q_i or "pooled Q" value for the ith data set, the crack size-time relationship given by Eq. (3-4), i.e., $a(0) = a(t)\exp(-Q_i t)$, is referred to as the "EIFS master curve" for the ith data set. In fact, the back-extrapolation for computing all EIFS sample values for the ith data set uses the same EIFS master curve.

3.3.3 Data Pooling

Suppose we have M different fractographic data sets generated under different test conditions (e.g., same type of load spectrum but different stress levels and % bolt load transfer). Then, we have M different "pooled Q" values; i.e., Q_i ($i = 1, 2, \ldots, M$), and M different EIFS master curves. Consequently, M EIFS data sets can be computed using the corresponding "pooled Q" value for each data set as described previously. These M data sets of EIFS values can be pooled together, referred to as "data pooling" (see Fig. 3-2), to define the EIFSD parameters. Pooling effectively increases the sample size and confidence in the EIFSD parameters. Likewise, this is a reasonable approach for justifying an EIFSD for more general applications.

The fractographic data pooling concept is conceptually illustrated in Fig. 3-6 using two fractographic data sets. The premise of data pooling is that each data set has a common EIFSD. For example, if the TTCIs for each data set are regressed backwards to time zero using the applicable EIFS master curve for each data set, the resulting EIFSs have the same EIFSD. In other words, the TTCI distribution for different fractographic data sets can be determined using the same EIFSD.

Thus, EIFS values for M data sets obtained previously can be pooled together and used to determine the EIFSD parameters, x_u, α and ϕ . The combined least square sums proce-

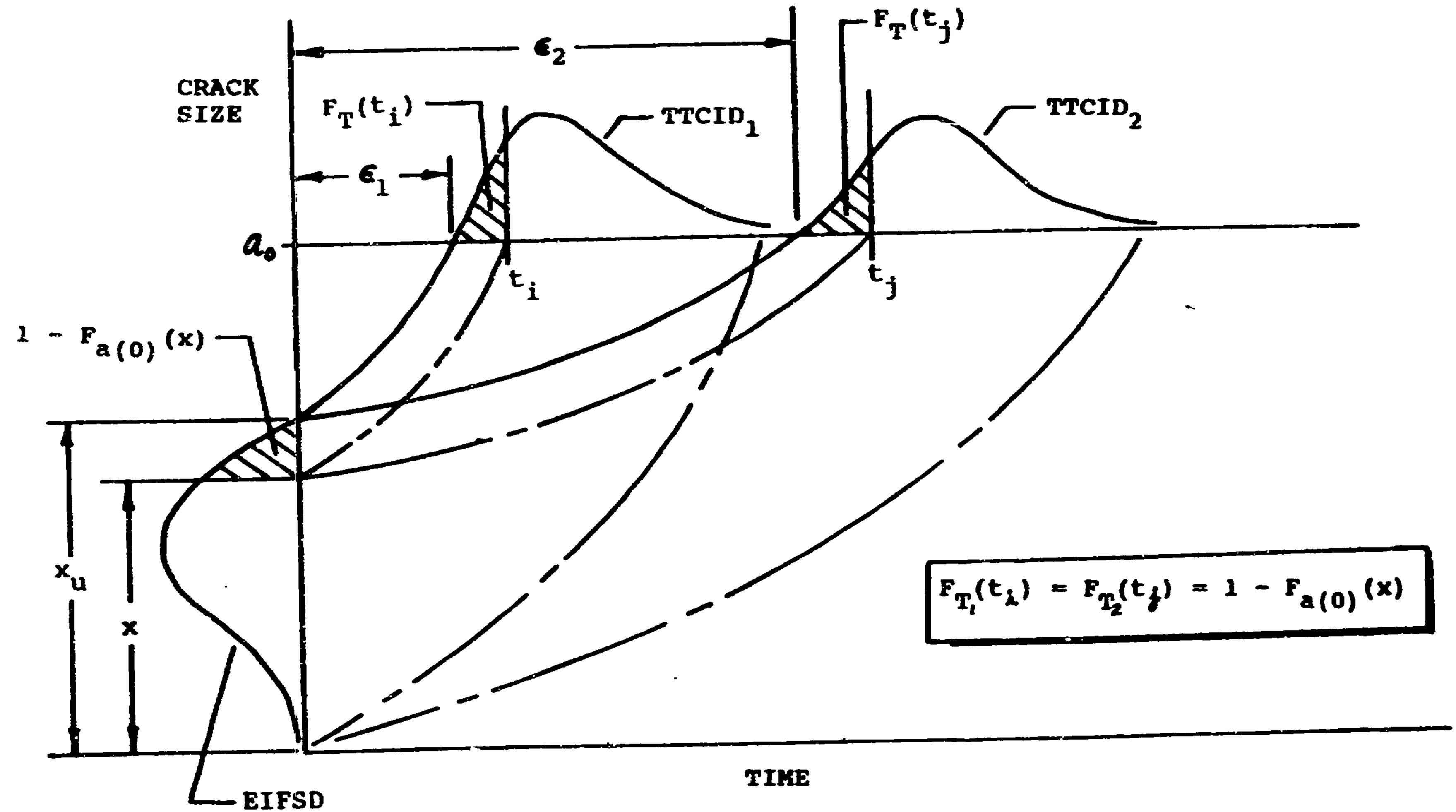


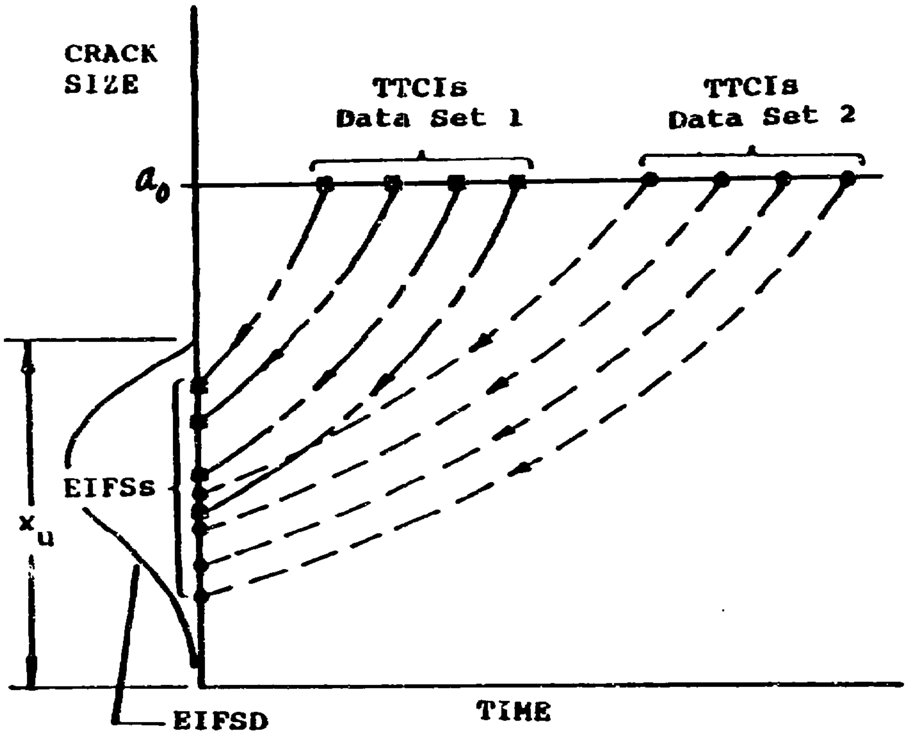
Figure 3-6. **Fractographic Data Pooling Concept.**

dure to be described later may be used to optimize the EIFSD parameters. The approach described above is referred to as the "EIFS fit" [2,3]. Another approach to determine the EIFSD parameters is a direct application of TTCI data sets in conjunction with applicable EIFS master curves (or back-extrapolation transformation) as described in Refs. 2 and 3. Such an approach is referred to as the "TTCI fit" [2,3]. Although there are subtle differences between the two approaches, either approach gives the same EIFSD parameters [3]. The two approaches are conceptually described in Fig. 3-7. An "EIFS fit" is recommended and is emphasized in the following because EIFS statistics (i.e., mean and standard deviation) provide a common baseline for comparing and cataloging "initial fatigue quality" data from various sources; whereas, TTCI statistics (i.e., mean and standard deviation) do not.

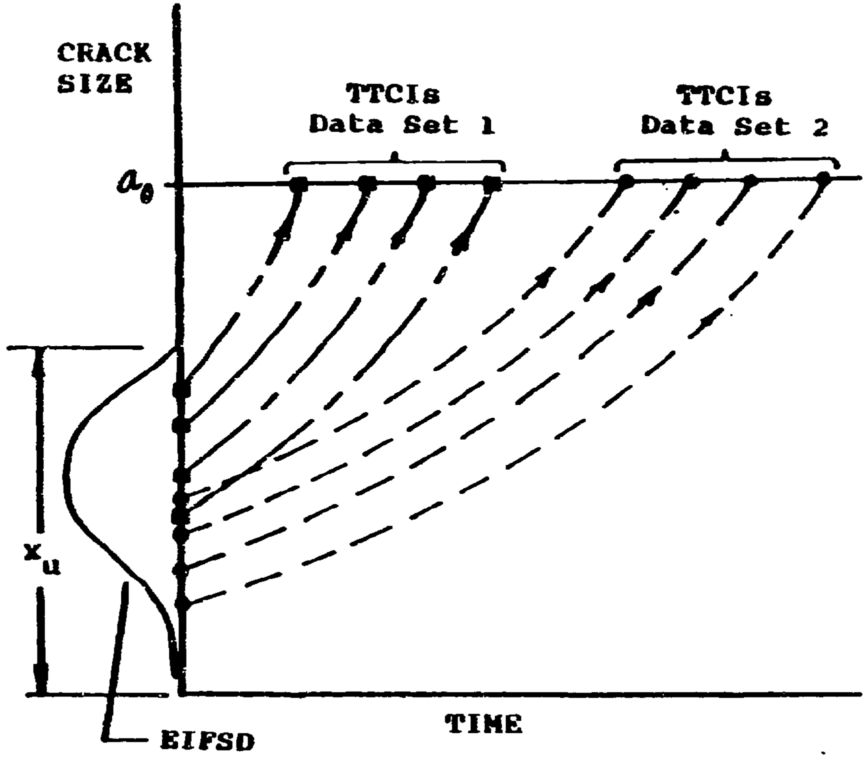
Software is available in Volume V [24] for implementing the data pooling procedure described in this section on an IBM or IBM-compatible PC.

3.3.4 Statistical Scaling Technique

The IFQ or EIFSD for fastener holes is defined for a "single hole population." Therefore, the fatigue cracking resistance of each fastener hole in each test specimen is accounted for in the definition of the EIFSD. Test specimens for acquiring fatigue crack growth data may have one or more fastener holes per specimen. Some specimens may or may not be fatigue tested to failure. Also, every fastener hole in each replicate test specimen may not contain a measurable fatigue crack or else the crack is too small or complex (e.g., multiple crack origins and branching) for fractographic analysis. A statistical scaling technique has been developed [2] for determining the EIFSD for a "single hole population" based on the largest fatigue crack per specimen. Hence, it



(a) Estimate EIFSD Parameters Using EIFSs



(b) Estimate EIFSD Parameters Using TTCIs

Figure 3-7. Two Different Philosophies for Estimating EIFSD Parameters Using Fractographic Data Pooling Procedures and DCGA.

is necessary to read only the fractographic results for the largest crack per specimen. Essential elements are conceptually described in Fig. 3-8. This technique is very general and is independent of the distribution functions used. It accounts for the number of fastener holes per test specimen in a given fractographic data set. It minimizes the fractographic reading requirements, permits a maximum utilization of the available fractographic data and allows for "mixing and matching" of fractographic data for the largest crack in specimens with a different number of holes.

Details of the statistical scaling technique developed are given in Volume I [2]. Essential features and key equations are summarized in the following.

Let the cumulative distribution of EIFS for a single hole population be denoted by $F_{a(0)}(x)$, and that of the EIFS based on the largest fatigue crack per specimen with ℓ fastener holes be denoted by $F_{a_\ell(0)}(x)$. Assuming that fatigue cracking in each fastener hole of a specimen is statistically independent of the other holes, $F_{a_\ell(0)}x)$ is related to $F_{a(0)}(x)$ through the following,

$$F_{a_\ell(0)}(x) = [F_{a(0)}(x)]^{\ell} \tag{3-8}$$

where ℓ = number of fastener holes per specimen. Similar expressions for the cumulative distribution of TTCI are given in Eqs. (3-9) and (3-10),

$$F_T(t) = 1 - [1 - F_{T_\ell}(t)]^{1/\ell} \tag{3-9}$$

$$F_{T_\ell}(t) = 1 - [1 - F_T(t)]^{\ell} \tag{3-10}$$

Notes

① Distribution of TTCI based on largest fatigue crack in 1 of ℓ fastener holes/specimen
② TTCID for "single hole population"
③ Distribution of EIFS based on the largest fatigue crack in 1 of ℓ fastener holes/specimen
④ EIFSD for "single hole population"

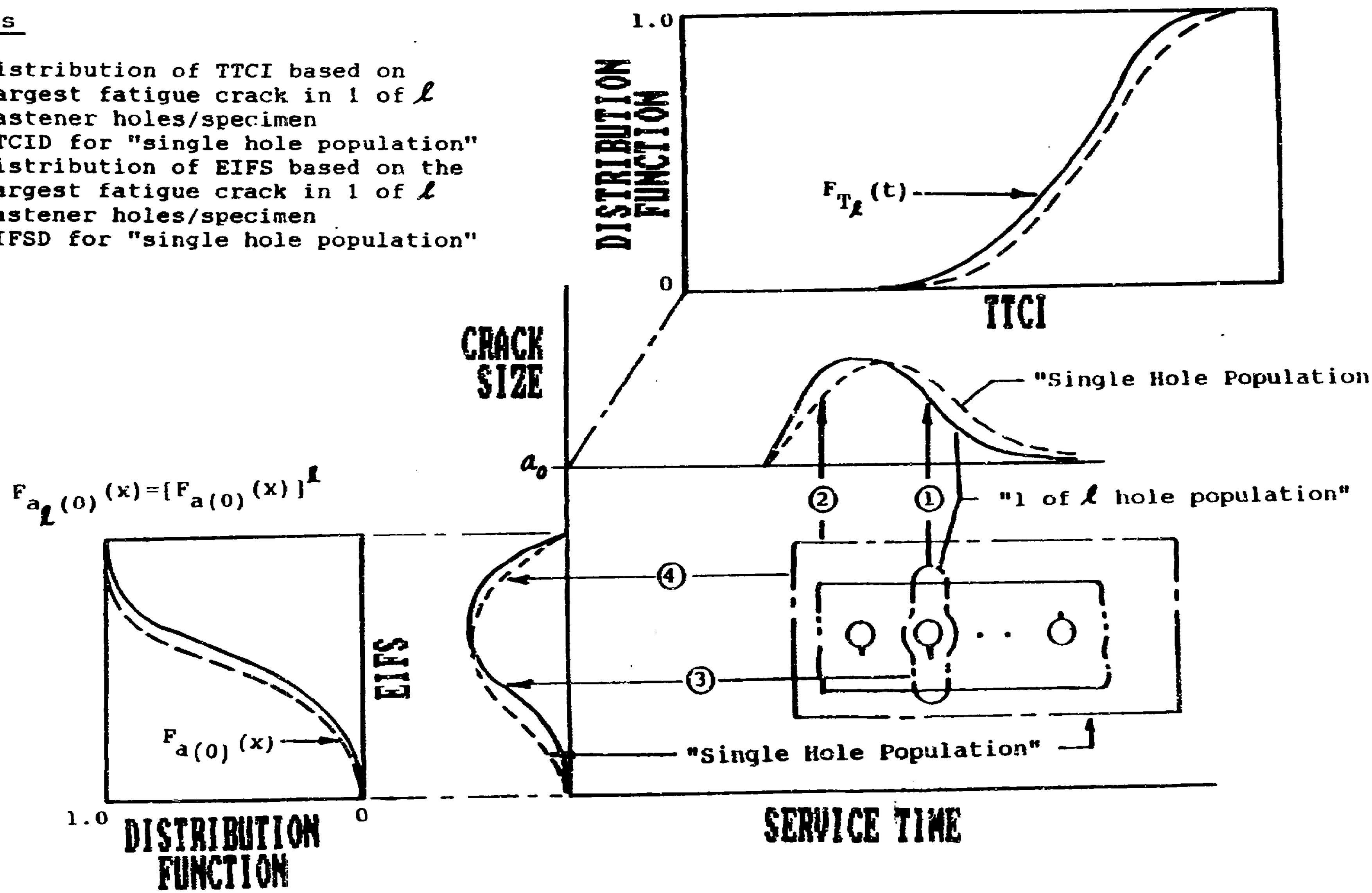


Figure 3-8. Statistical Scaling Concept for "Single Hole Population".

where $F_T(t)$ = cumulative distribution of TTCI for a single hole population, and $F_{T_\ell}(t)$ = cumulative distribution of the minimum TTCI per specimen with ℓ holes.

In a similar manner, let $F_{a(t)}(x)$ denote the cumulative distribution of crack size at any time t for a single hole population and $F_{a_\ell(t)}(x)$ denote the cumulative distribution of crack size at any time t based on the largest crack size in a specimen with ℓ holes. Then, $F_{a(t)}(x)$ is related to $F_{a_\ell(t)}$ as follows.

$$F_{a_\ell(t)}(x) = [F_{a(t)}(x)]^\ell \qquad (3\text{-}11)$$

The simple scaling technique described in this section has been incorporated into the procedure for estimating the EIFSD parameters. Computer software for the IBM-compatible PC is available for estimating the EIFSD parameters, and for checking goodness-of-fit [24]. The validity of the statistical scaling technique is evaluated and demonstrated in Volume II [3].

3.3.5 Combined Least Square Sums Approach (CLSSA)

With the procedures described previously, we have M EIFS data sets corresponding to M available fractographic data sets. However, these M EIFS data sets are not necessarily homogeneous, since each data set may have a different scaling factor. For instance, the ith EIFS data set may represent the largest crack per specimen with ℓ_i holes, whereas the jth EIFS data set may represent the largest crack per specimen with ℓ_j holes, where $\ell_i \neq \ell_j$. In this case, the ith and jth EIFS data sets are non-homogeneous. Hence, methods should be developed to utilize such data sets to determine the EIFSD parameters. In this connection, a method has been developed in Vol. I [2], referred to as the "combined least square sums approach". This approach enables one to "mix and match" these inhomogeneous EIFS data sets for the determination of EIFSD parameters. Step-by-step procedures are described in the following for estimating the EIFSD parameters of the Weibull-compatible distribution (i.e., α and ϕ for a given x_u).

1. Define the scaling factor for each EIFS data set (see Section 3.3.4). The scaling factor for the ith EIFS data set is denoted by ℓ_i, i.e., ℓ_i is the number of fastener holes per replicate specimen in data set i.

2. Rank the EIFSs for each data set separately. Let x_{ij} be the jth smallest EIFS value in the ith data set.

3. Assume the Weibull compatible distribution function, Eq. (3-1) is used to represent the EIFSD. Other suitable distribution functions could be used, for example, the lognormal compatible, lognormal and two-parameter Weibull distribution functions.

4. Determine the Weibull compatible EIFSD parameters in Eq. (3-1) i.e., α and ϕ for an assumed x_u that is the EIFS upper bound limit. x_u is chosen with the following recommended constraints for clearance-fit fastener holes: largest EIFS value in M data sets $\leq x_u \leq 0.05"$. Then, compute α and ϕ using Eqs. (3-12) and (3-13), respectively.

$$\alpha = \frac{\sum_{i=1}^{M} N_i \sum_{i=1}^{M} \sum_{j=1}^{N_i} X_{ij} Y_{ij} - \sum_{i=1}^{M} \sum_{j=1}^{N_i} X_{ij} \sum_{i=1}^{M} \sum_{j=1}^{N_i} Y_{ij}}{\sum_{i=1}^{M} N_i \sum_{i=1}^{M} \sum_{j=1}^{N_i} X_{ij}^2 - \left[\sum_{i=1}^{M} \sum_{j=1}^{N_i} X_{ij} \right]^2} \tag{3-12}$$

$$\phi = exp \left\{ \frac{\alpha \sum_{i=1}^{M} \sum_{j=1}^{N_i} X_{ij} - \sum_{i=1}^{M} \sum_{j=1}^{N_i} Y_{ij}}{\alpha \sum_{i=1}^{M} N_i} \right\} \tag{3-13}$$

In Eqs. (3-12) and (3-13), X_{ij}, Y_{ij} are defined as follows,

$$\left.\begin{aligned} X_{ij} &= \ln\ln(x_u/x_{ij}) \\ Y_{ij} &= \ln\left\{-(1/\ell_i)\ln\left[\frac{j}{N_i+1}\right]\right\} \end{aligned}\right\} \quad (3\text{-}14)$$

where, M = number of EIFS data sets used to determine the EIFSD parameters, N_i = the total number of EIFS values for the ith data set and j = rank in ascending order of the EIFS value in the ith data set, i.e., j = 1, 2..., N_i.

Software is available in Volume V [24], for an IBM or IBM-compatible PC, for implementing the CLSSA described above.

3.3.6 Optimization of EIFSD Parameters and Goodness-Of-Fit

The Weibull compatible EIFSD parameters (i.e., α, ϕ, and x_u) in Eq. (3-1) need to be optimized. Also, the candidate EIFSD should be tested for "goodness-of-fit". These aspects are discussed in the following.

An iterative procedure, based on the total standard error (TSE), was developed [2] and evaluated [3] for optimizing the EIFSD parameters for the Weibull compatible distribution function. This procedure, conceptually described in Fig. 3-9, can be used in conjunction with CLSSA described in Section 3.3.5 and can be implemented using software filename = "WCIFQ" from Volume V [24].

The optimization procedure is as follows.

1. Assume a value for the EIFS upper bound limit, x_u, within the recommended range for clearance-fit fastener holes (i.e., largest EIFS value in M data sets $\leq x_u \leq 0.05$").

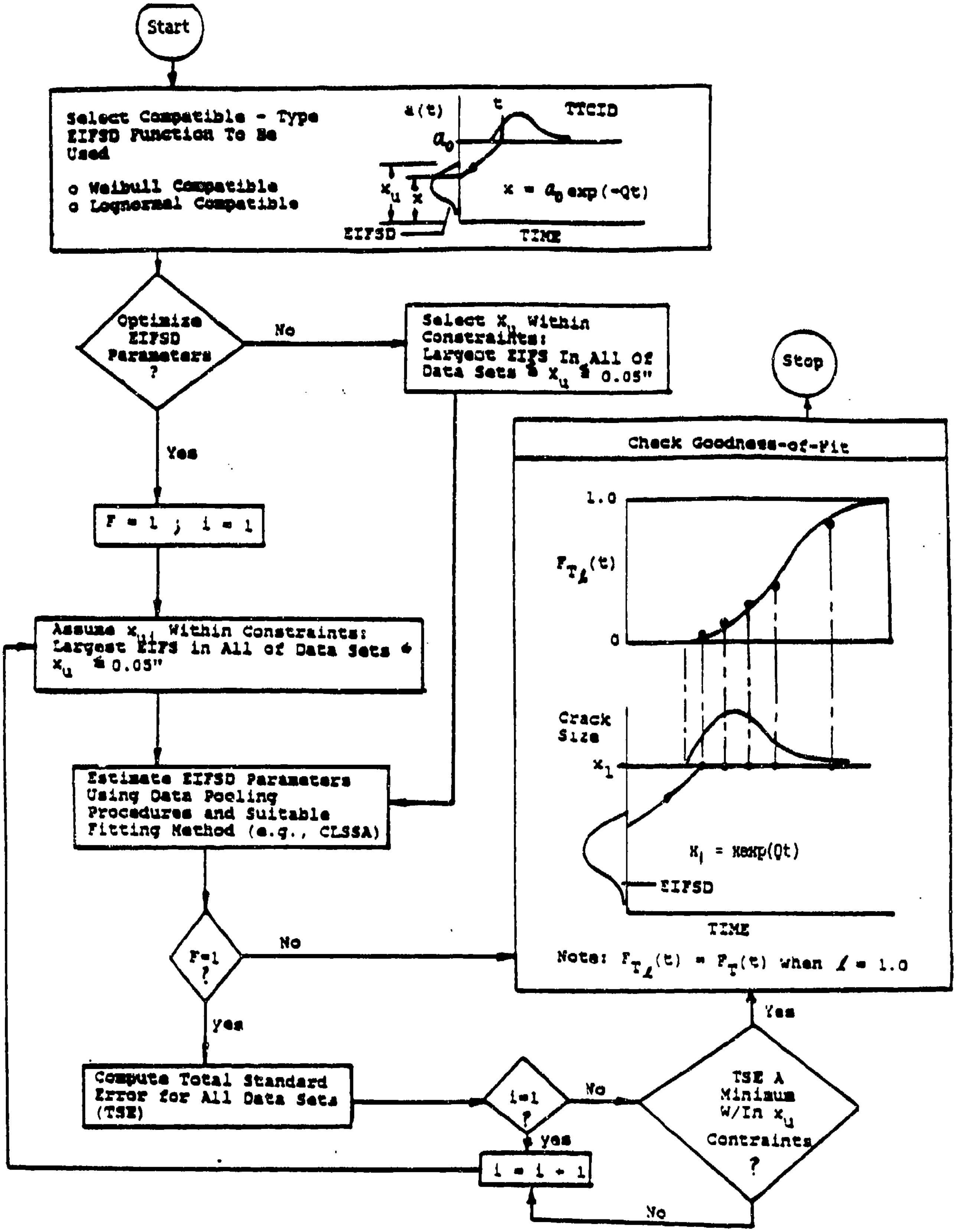


Figure 3-9. General Procedure for Optimizing EIFSD Parameters and Checking Goodness-of-Fit for Compatible Type EIFSD Function.

2. Determine α and ϕ for the assumed x_u value using the CLSSA described in Section 3.3.5 and Eqs. (3-12) and (3-13), respectively.

3. Compute the total standard error, TSE, for M EIFS data sets using the α, ϕ and x_u values from Steps 1 and 2 above as follows.

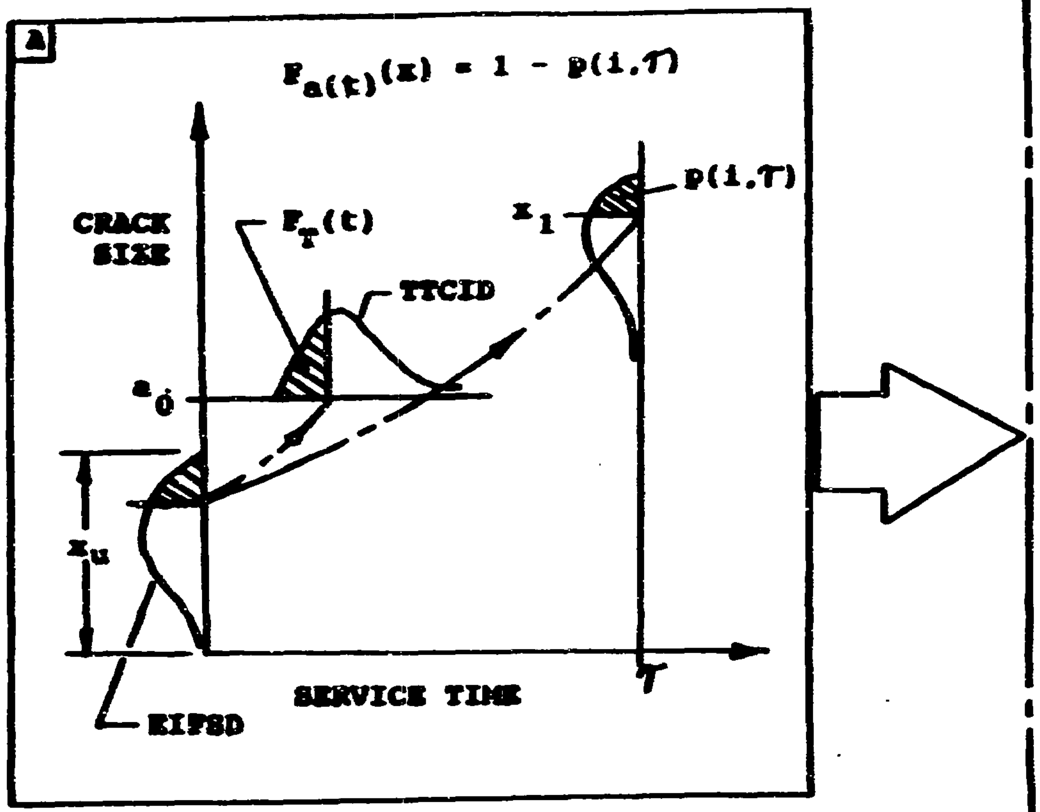
$$TSE = \sqrt{\frac{\sum_{i=1}^{M} \sum_{j=1}^{N_i} \left\{ j/(N_i + 1) - exp\left\{ - l_i \left[\frac{ln\,(x_u/x_j)}{\phi} \right]^{\alpha} \right\} \right\}^2}{\sum_{i=1}^{M} N_i}} \qquad (3\text{-}15)$$

All terms in Eq. (3-15) are the same as those defined for Eqs. (3-12) and (3-13).

4. Repeat Steps 1-3 for different x_u values and the optimal (α, ϕ, x_u) is obtained when the corresponding TSE is a minimum. Verify the goodness-of-fit for the resulting EIFSD using the fractographic data sets that have been used to estimate the EIFSD parameters. For example, correlate theoretical predictions for (i) the probability of crack exceedance, $p(i,\tau)$, at a given service time, τ, and (ii) the cumultive distribution of service time to reach any crack size x_1, $F_{T(x_1)}(t)$, with actual fractographic results for those data sets that have been used to define the IFQ, see Fig. 3-10. Other fractographic data sets (e.g., for different stress levels, load spectra, % bolt load transfer, etc.) that have not been used to estimate the EIFSD parameters can also be used to justify the candidate EIFSD for durability analysis.

3.4 TWO-SEGMENT DETERMINISTIC-STOCHASTIC CRACK GROWTH APPROACH (DCGA-SCGA)

The EIFS distribution established previously will serve as a basis from which the extent of damage for a durability



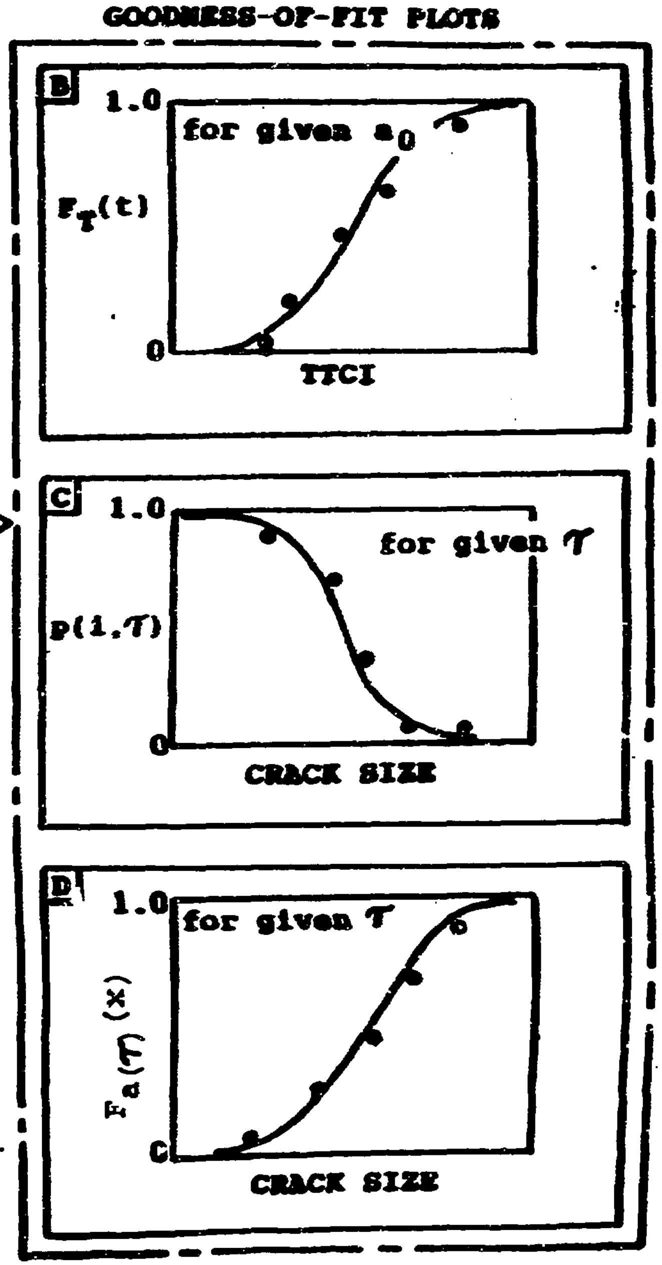


Figure 3-10. Elements for Justifying EIFSD and Goodness-of-Fit Plots.

critical component at any service time will be predicted. This is accomplished by growing the entire EIFS population (or distribution) forward under the design loading spectra. In growing the EIFSD forward, the computation of the crack growth damage accumulation in service is divided into two segments for simplicity. In the first segment in which the crack size is smaller than the reference crack size a_0 for TTCI, a deterministic crack growth rate model, Eq. (3-16), is used.

$$\frac{da(t)}{dt} = Q_1[a(t)]^{b_1};\ a(t) < a_0 \qquad (3\text{-}16)$$

In Eq. (3-16), Q_1 and b_1 are empirical-based constants depending on the expected service loading spectrum. They can be obtained based on either applicable fractographic data or crack growth predictions using a suitble analytical crack growth program [e.g., 31,32]. Since EIFS values are determined from fractographic data in the AL-AU range by back-extrapolation using the deterministic crack growth approach, the EIFS distribution must be grown forward up to the reference crack size a_0, that is usually equal to AU, based on the deterministic crack growth approach.

The following stochastic crack growth rate model is used for crack sizes > a_0

$$da(t)/dt = XQ_2[a(t)]^{b_2};\ a(t) > a_0 \qquad (3\text{-}17)$$

in which X is a lognormal random variable with a median of one; Q_2 and b_2 are crack growth rate parameters depending on the service load spectrum. Equation (3-17) accounts for the crack growth rate variability and is referred to as the "lognormal random variable model" proposed by Yang et al [25,26,28,33-36].

The probability density function of the lognormal random variable X with a median 1.0 is given by

$$f_X(u) = \frac{\log e}{\sqrt{2\pi}\, u\, \sigma_z} \exp\left\{-\frac{1}{2}\left[\frac{\log u}{\sigma_z}\right]^2\right\}; \quad u \geq 0$$

$$= 0 \qquad ; \quad u < 0 \tag{3-18}$$

in which σ_z is the standard deviation of the normal random variable $Z = \log X$. Equation (3-18) is used when σ_z is estimated using the log to base 10 form. If σ_z is based on the natural log form, $f_X(u)$ given in Eq. (3-19) should be used.

$$f_X(u) = \frac{1}{\sqrt{2\pi}\, u\, \sigma_z} \exp\left\{-\frac{1}{2}\left[\frac{\ln u}{\sigma_z}\right]^2\right\}; \quad u \geq 0$$

$$= 0 \qquad ; \quad u < 0 \tag{3-19}$$

Note that σ_z based on the log to base 10 is equal to that based on the natural log divided by the natural log of 10. Details for estimating σ_z are given elsewhere [2,3].

Let T be the time for the EIFS, $a(0)$, to reach a reference crack size a_0. Then, integrating Eq. (3-16) from $t = 0$ to $t = T$ for $b_1 = 1$, one obtains

$$T = a_1^{-1} \ln[a_0/a(0)] \tag{3-20}$$

in which it is understood that $a(T) = a_0$.

In the region where $a(\tau) > a_0$ (or $\tau > T$), Eq. (3-17) is integrated with $b_2 = 1$ from $t = T$ to $t = \tau$ (or from $a(T) = a_0$ to $a(t) = a(\tau)$; with the result

$$\tau = \mathcal{T} - (\chi Q_2)^{-1} \ln[a(\mathcal{T})/a_0]\ ;\ a(\mathcal{T}) > a_0 \tag{3-21}$$

Equating Eqs. (3-20) and (3-21) leads to the following relation between $a(\mathcal{T})$ and $a(0)$

$$a(0) = a_0 \exp(-Q_1 \mathcal{T})[a(\mathcal{T})/a_0]^{\gamma/\chi}\ ;\ a(\mathcal{T}) > a_0 \tag{3-22}$$

in which

$$\gamma = Q_1/Q_2 \tag{3-23}$$

When the crack size, $a(\mathcal{T})$, at any service time $\mathcal{T}$ is smaller than a_0, the relation between $a(\mathcal{T})$ and $a(0)$ is obtained by integrating Eq. (3-16) for $b_1 = 1$ from $t = 0$ to $t = \mathcal{T}$ as follows:

$$a(0) = a(\mathcal{T}) \exp(-Q_1 \mathcal{T})\ ;\ a(\mathcal{T}) < a_0 \tag{3-24}$$

Equations (3-22) and (3-24) show the relation between the crack size in service $a(\mathcal{T})$ and the EIFS $a(0)$. They will be used to transform the EIFSD to the distribution of the crack size $a(\mathcal{T})$ later.

3.4.1 Probability of Crack Exceedance in Service

The probability that a crack in the ith stress region will exceed any specified crack size x_1 at any service time $\mathcal{T}$ is referred to as the probability of crack exceedance, denoted by $p(i, \mathcal{T})$. Depending on the crack size of interest x_1, the crack exceedance probability, $p(i, \mathcal{T})$, can be derived in the following manner.

(1) When the crack size of interest x_1 is smaller than the reference crack size a_0, the distribution function $F_{a(\tau)}(x_1) = P[a(\tau)<x_1]$ of the crack size, $a(\tau)$, for $x_1<a_0$ can be derived from the distribution function of a(0) through the transformation of (Eq. 3-24)

$$F_{a(\tau)}(x_1) = F_{a(0)}[y(x_1;\tau)] \tag{3-25}$$

in which

$$y(x_1;\tau) = x_1 \exp(-Q_1 \tau) \tag{3-26}$$

The crack exceedance probability, $p(i,\tau)$, is given by

$$\begin{aligned} p(i,\tau) &= P[a(\tau) > x_1] = 1 - F_{a(\tau)}(x_1) \\ &= 1 - F_{a(0)}[y(x_1;\tau)]; \; x_1 \le a_0 \end{aligned} \tag{3-27}$$

where $F_{a(0)}(x)$ is the distribution function of EIFS, a(0), given by Eq. (3-1) or other suitable distribution functions.

(2) When the crack size of interest x_1 is larger than a_0, the conditional distribution function of $a(\tau)$ at any service time τ, given X=u, can be derived from that of a(0) through the transformation of (Eq. 3-22). Then, the unconditional distribution function, $F_{a(\tau)}(x_1)$, of $a(\tau)$ can be obtained using the theorem of total probability; with the result.

$$F_{a(\tau)}(x_1) = \int_0^{\infty} F_{a(0)}[G(x_1;\tau|X=u)] f_X(u)du \tag{3-28}$$

in which the lognormal probability density function $f_X(u)$ is given by Eq. (3-18) or (3-19) and

$$G(x_1;\tau|X=u) = a_0 \exp(-Q_1\tau)[x_1/a_0]^{1/u} \qquad (3\text{-}29)$$

The crack exceedance probability, $p(i,\tau)$, for $x_1 > a_0$ is given by $p(i,\tau) = 1 - F_{a(\tau)}(x_1)$, i.e.,

$$p(i,\tau) = 1 - \int_0^\infty F_{a(0)}[G(x_1;\tau|X=u)] f_X(u)\,du \qquad (3\text{-}30)$$

When the Weibull compatible distribution, (Eq. 3-1), is used for the EIFSD, the condition that $F_{a(0)}[G(x_1;\tau|X=u)] = 1$ for $G(x_1;\tau|X=u) > x_u$ should be reflected in the computer program [24] for computing the crack exceedance probability $p(i,\tau)$, (Eq. 3-30.)

3.4.2 Cumulative Distribution of Service Time To Reach any Specified Crack Size

Let $T(x_1)$ be the time for a crack to reach any given crack size x_1 and $F_{T(x_1)}(\tau)$ be the corresponding cumulative distribution function, i.e., $F_{T(x_1)}(\tau) = P[T(x_1) < \tau]$. The distribution function of $T(x_1)$ is the probability that the crack will reach a crack size x_1 before service time τ. Such a probability is equal to the probability that the crack size $a(\tau)$ at service time will exceed x_1, which is simply the probability of crack exceedance, Hence,

$$\begin{aligned} F_{T(x_1)}(\tau) &= P[T(x_1) \le \tau] \\ &= P[a(\tau) \ge x_1] = p(i,\tau) \end{aligned} \qquad (3\text{-}31)$$

Consequently, $F_{T(x_1)}(\tau)$ is obtained for any given crack size x_1 by computing the crack exceedance probability, $p(i,\tau)$, at different values of service time τ.

The cumulative distribution of service time, $F_{T(x_1)}(\tau)$, for a crack to reach any given crack size x_1 is determined using (Eq. 3-31.) $F_{T(x_1)}(\mathcal{T})$ is obtained for $x_1 < a_0$ and for $x_1 > a_0$ by computing $p(i,\mathcal{T})$ at different service times, $\mathcal{T}$, using Eq. (3-27) and (3-30.) respectively.

3.5 DURABILITY ANALYSIS PROCEDURE

The durability analysis procedure for implementing the two-segment DCGA-SCGA described in Fig. 3-4 includes the following basic steps.

1. Decide at what level the durability analysis will be performed (e.g., single part, several different parts, component, etc.).

2. Determine which structural details will be included in the durability analysis (e.g., fastener holes, lugs, cutouts, fillets, etc.).

3. Determine the IFQ or suitable EIFSD for each type of structural detail to be considered as described in Section 3.3.

4. For each part, component, etc., group the structural details by type into m stress regions where the maximum stress in each region may reasonably be assumed to be equal for every location or detail (e.g., fastener hole).

5. Determine service crack growth parameters Q_1, Q_2 and σ_z for each stress region.

6. Compute the probability of crack exceedance, $p(i,\mathcal{T})$, at a given service time $\mathcal{T}$ for each stress region.

7. If desired, compute the cumulative distribution of service time to reach a given crack size x_1, $F_{T(x_1)}(\mathcal{T})$. This computation is optional.

8. Estimate the extent of damage mean ($P = 0.5$) and upper bound limit for selected exceedance probability (e.g., $P = 0.05$).

Essential equations and details for implementing the above steps are given in the following subsections.

Durability analysis guidelines are given in Section IV. Procedures and methods are illustrated in Section V and elsewhere [2-7,24-29]. Documented software, with a plotting capability, is available in Volume V [24] for an IBM or IBM-compatible PC for implementing the durability analysis. This software is briefly described in Section VI.

3.5.1 Service Crack Growth Parameters Q_1, Q_2 and σ_z

The relation between the crack size, $a(\tau)$, at any service time τ and the EIFS, $a(0)$, such as Eqs. (3-22) and (3-24), is referred to as the "service crack growth master curve" (SCGMC). The SCGMC in each stress region is determined by either available fractographic results or LEFM crack growth analysis. in the latter case, the LEFM crack growth computer program [e.g., 31,32] is "tuned" or "curve-fitted" to the EIFS master curve in the AL-AU crack size region where baseline fractographic data are available. Normal assumptions for the crack shape and geometry are reflected in the crack growth analysis. Then, the SCGMC is fitted by Eq. (3-16) for the crack size smaller than a_0 to determine the parameters Q_1 and b_1, and by Eq. (3-17) for the crack size larger than a_0 to determine parameters Q_2 and b_2 (with $X = 1.0$), using the least squares fit procedure. The special case $b_1 = b_2 = 1.0$ can be used in Eqs. (3-16) and (3-17), which has been shown to be quite reasonable for durability analyses [1-3,5-7,17,21,22, 25,29].

If suitable fractographic results are available, it may be feasible to develop expressions for Q_1 (Eq. 3-16) and Q_2 (Eq. 3-17) in terms of the maximum stress level using an empirical model proposed by Yang and Manning [1-3,5,16].

$$Q_i = C\sigma_i^V \tag{3-32}$$

In Eq. (3-32,) Q_i = service crack growth parameter either Q_1 or Q_2 for the ith stress region, σ_i = maximum stress level in the ith stress region, and C and V are empirical constants. Both C and V can be determined from available base-line data or suitable analytical crack growth results for Q_i versus σ_i (i = 1, 2, ..., m) using a least square fit procedure.

The following notations are used to determine the standard deviation, σ_z, shown in Eqs. (3-18) and (3-19) using a particular fractographic data set. Let m = the total number of fatigue cracks in the fractographic data set, N_j = number of da(t)/dts versus a(t)s in the AL-AU range for the jth fatigue crack, $N = \sum_{j=1}^{m} N_j$ = total number of [da(t)/dt, a(t)] pairs in the AL-AU range, $(da(t)/dt)_{jk}$ = the kth crack growth rate value for the jth fatigue crack, $a_j(t_k)$ = crack size for the jth fatigue crack at the kth service time t_k (i.e., k = 1, 2, ..., N_j), Q_j = crack growth rate parameter for the jth fatigue crack defined by Eq. 3-5 and Q = "pooled Q" value for the fractographic data set defined by Eq. (3-6) in which Q = Q_i.

The standard deviation, σ_z, for the ith stress region shown in Eq. (3-18) and (3-19) reflects the "log to base 10 form" and the "natural log form," respectively. If the "log to base 10 form" is used, σ_z is computed from either Eq. (3-33) or (3-34.)

$$\sigma_z = \sqrt{\frac{1}{N}\sum_{j=1}^{m}\sum_{k=1}^{N_j}\left[\log(da(t)/dt)_{jk} - \log Q - \log a_j(t_k)\right]^2} \tag{3-33}$$

$$\sigma_z = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left[\log(Q_j/Q)\right]^2} \tag{3-34}$$

If the "natural log form" is used, σ_z is computed using either Eq. (3-35) or (3-36).

$$\sigma_z = \sqrt{\frac{1}{N}\sum_{j=1}^{m}\sum_{k=1}^{N_j}\left[\ln(da(t)/dt)_{jk} - \ln Q - \ln a_j(t_k)\right]^2} \tag{3-35}$$

$$\sigma_z = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left[\ln(Q_j/Q)\right]^2} \tag{3-36}$$

3.5.2 Probability of Crack Exceedance

Given Q_1, Q_2 and σ_z, the probability of crack exceedance, $p(i, \tau)$, for each stress region, i, at any service life, τ, can be computed as described in Section 3.4.1.

3.5.3 Cumulative Distribution of Service Time To Reach Any Specified Crack Size

The cumulative distribution of service time to reach any crack size x_1, $F_{T(x_1)}(\tau)$, can be computed for the desired stress regions. This computation is optional since the results are not needed for estimating the extent of damage. The equations for computing $F_{T(x_1)}(\tau)$ are given in Section 3.4.2.

3.5.4 Statistical Estimation for Extent of Damage

The extent of damage can be defined by the statistics or distribution of the number of structural details or ligaments in the durability-critical component expected to exceed specified crack size limits at a given service time. From a functional impairment standpoint, the extent of damage may be interpreted as the number of locations where the accumulated crack size exceeds limiting crack sizes for functional impairment. For example, a through-the-thickness crack in a fuel tank may cause fuel leakage and the dimension between adjacent structural details may be considered as a crack size limit for ligament breakage. The mean and upper bound limit (see Fig. 3-5) for the extent of damage can be estimated for selected exceedance probabilities as follows.

The number of details, $N(i, \tau)$, in the ith stress region with a crack size greater than x_1 at the service time τ, is a statistical variable. The mean value, $\bar{N}(i, \tau)$, and the standard deviation, $\sigma_N(i, \tau)$, are determined using the Binomial distribution [50].

$$\bar{N}(i,\tau) = N_i\, p(i,\tau) \tag{3-37}$$

$$\sigma_N(i,\tau) = \{N_i\, p(i,\tau)[1 - p(i,\tau)]\}^{1/2} \tag{3-38}$$

in which N_i denotes the total number of details in the ith stress region. The average number of details with a crack size exceeding x_1 at the service time τ for m stress regions, $\bar{L}(\tau)$, and the standard deviation, $\sigma_L(\tau)$, can be computed using Eqs. (3-39) and (3-40), respectively.

$$\bar{L}(\tau) = \sum_{i=1}^{m} \bar{N}(i,\tau) \tag{3-39}$$

$$\sigma_L(\tau) = \left\{\sum_{i=1}^{m} \sigma_N^2(i,\tau)\right\}^{1/2} \tag{3-40}$$

Equations (3-39) and (3-40) can be used to quantify the extent of damage for a single detail, a group of details, a part, a component, or an airframe. $\bar{L}(\tau)$ approximately corresponds to a 50% probability. Upper and lower bound limits for the "extent of damage" can be estimated using the Binomial distribution, e.g., $\bar{L}(\tau) \pm Z\sigma_L(\tau)$, with Z being the number of standard deviations, from the mean, $\bar{L}(\tau)$. For example, $Z = 1.65$ and $Z = -1.65$ correspond to exceedance probabilities of $P = 0.05$ and 0.95, respectively. Equations (3-37) to (3-40) are valid assuming that the crack growth accumulation for each detail is statistically independent [50].

SECTION IV

DURABILITY ANALYSIS GUIDELINES

Durability analysis guidelines are presented in this section for the following: (1) acquisition and utilization of fractographic data, (2) determination of suitable EIFSD for durability analysis, (3) determination of service crack growth master curves for small and large crack size regions, (4) estimation of standard deviation, σ_z for the large crack size region, (5) initial flaw size considerations, and (6) extent of damage. Practical aspects are emphasized.

4.1 ACQUISITION AND UTILIZATION OF FRACTOGRAPHIC DATA

Guidelines are presented in this section for: (1) test specimens, (2) fatigue testing, (3) fractography, (4) utilizing existing fractographic data and (5) screening/censoring fractographic data.

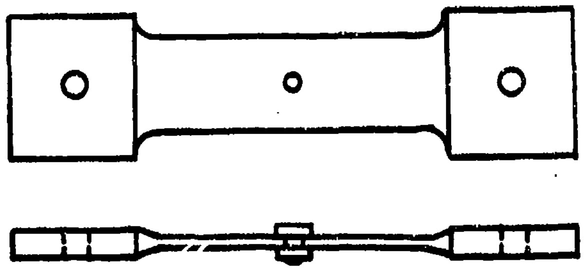
Initial fatigue quality (IFQ) data can be acquired for various materials and structural details as a part of the Aircraft Structural Integrity Program (ASIP) effort. Specimens tested under ASIP can provide data applicable to both "durability" and "damage tolerance". For example, if structural details in test specimens are not preflawed, "natural fatigue crack" data can be used not only to estimate the IFQ of structural details but also to satisfy durability and damage tolerance data requirements. Depending on the degree of confidence desired and circumstances, additional tests and fractographic evaluations may be desirable to estimate the IFQ. In the future, ASIP test plans should be designed to satisfy the needs for initial fatigue quality, durability and damage tolerance. This approach will minimize the IFQ data acquisition costs with a minimal impact on schedule.

4.1.1 Test Specimens

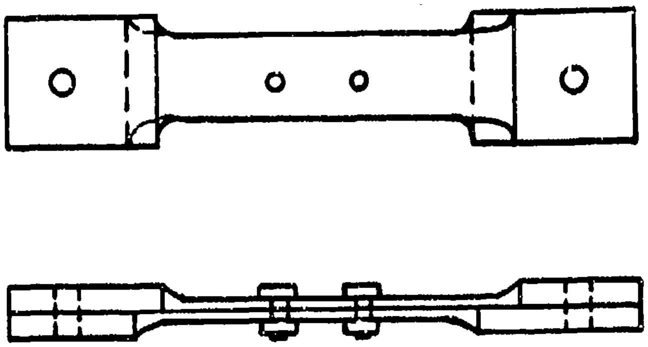
Initial fatigue quality (IFQ) data can be acquired from suitable fractographic results for the type of structural detail to be reflected in the durability analysis (e.g., fastener holes, cutouts, lugs, fillets, etc.). So far, IFQ of clearance-fit straight-bore and countersunk fastener holes has been primarily investigated [3,5-7,17,30-22,27,28,30]. Such investigations were concerned with clearance-fit fasteners in holes without special life enhancement features (e.g., cold working, interference fit fasteners, force-fit bushings, etc.).

The test specimen(s) used to acquire the IFQ data should include the type of structural detail for which the IFQ is sought. Also, the structural detail should reflect the applicable manufacturing, assembly and processing methods, including fastener hole life enhancement considerations. Further research is needed to develop/evaluate appropriate test specimen designs for acquiring IFQ data for cutouts, fillets, lugs, etc.

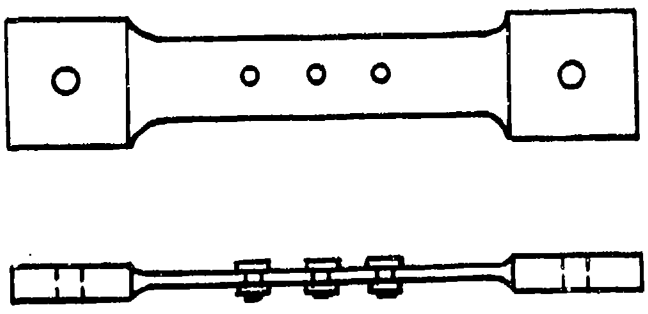
Various types of specimen have been previously used to acquire IFQ data for clearance-fit fastener holes [e.g., 37-39]. Three such specimen configurations are shown in Fig. 4-1. Here are a few comments about these specimen based on our experience. The simple dog-bone specimen shown in Fig. 4-1(a) with a single fastener hole and a bolt installed is best suited for acquiring the IFQ data. The double-reversed dog-bone specimen in Fig. 4-1(b) is simple for fatigue test to acquire the fractographic data. However, there is no way to accurately control the amount of bolt load transfer since the percent of bolt load transfer depends on the fastener-hole fit and the applied load level. A multi-hole type specimen, such as that shown in Fig. 4-1(c), is potentially



(a) No Bolt Load Transfer Specimen



(b) Double Reversed Dog-Bone Specimen Design



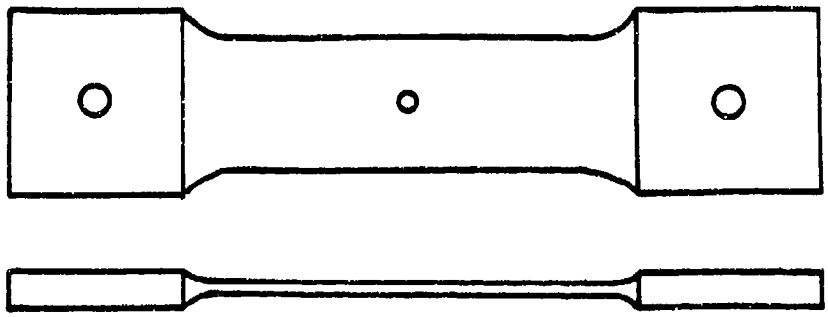
(c) Multi-Hole No Bolt Load Transfer Design

Figure 4-1. Common Types of Specimens Used for Acquiring IFQ Data for Fastener Holes.

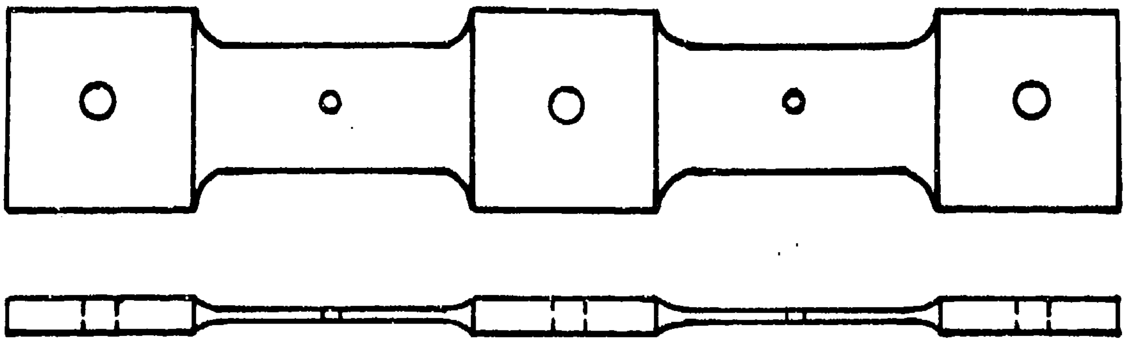
attractive for acquiring the IFQ data, however, it has the following limitations or shortcomings.

Fatigue cracks may initiate sooner in one hole than another. Ideally, one may assume that each fastener hole in the specimen of Fig. 4-1(c) is equally stressed until failure occurs. However, our experimental results [37-39] show that each hole may not be equally stressed during spectrum fatigue testing although the fastener holes are spaced far enough apart to minimize the effects of adjacent holes on the crack initiation and crack growth in neighboring holes. There is apparently some interaction between the fatigue cracks in adjacent holes for the larger fatigue cracks. The three-hole specimen designs shown in Fig. 4-1(c) may be reasonable for acquiring small fatigue crack data, but it is not recommended for acquiring large fatigue crack growth results in which there may be some interaction effect between adjacent holes.

Three types of specimen are recommended for acquiring IFQ data for fastener holes as shown in Fig. 4-2. In Fig. 4-2(a) the simple dog-bone specimen with a single fastener hole is well suited for acquiring IFQ data. The two-for-one specimen shown in Fig. 4-2(b) is also attractive for acquiring fatigue cracking data. For example, the test specimen can be fatigue tested to failure through one fastener hole. Then, the specimen is reworked by sawing off the broken piece and making an end lug out of the center built up area. Testing is continued until failure occurs in the second hole. When bolt load transfer is to be accounted for in the IFQ representation of the specimen, the specimen design shown in Fig. 4-2(c) is well suited. With this design, the basic specimen can be the same as that shown in Fig. 4-2(a). The only difference is that a loading bar is used to directly load the bolt in the center hole (either in double or single shear). Both the lug end and the loading bar are connected to separate loading rams which are synchronized for spectrum fatigue

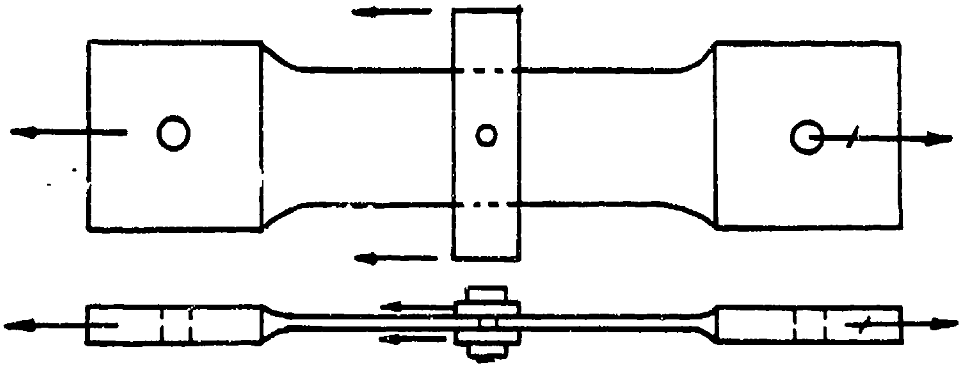


(a) No Bolt Load Transfer Dog-Bone Specimen



(b) Two-For-One No-Bolt Load Transfer Dog-Bone Specimen

(Use double or single shear configuration)



(c) Dog-Bone Specimen With Bolt Load Transfer

Figure 4-2. Recommended Specimen Types for Acquiring IFQ Data.

testing.

The biggest shortcoming of the double-reversed dog-bone specimen (see Fig. 4-1(b)) for acquiring IFQ data under bolt load transfer conditions is that the amount of bolt load transfer varies and cannot be controlled. The recommended bolt load transfer specimen design shown in Fig. 4-2(c) requires a more complicated test setup and more expensive testing costs. However, the dog-bone specimen shown in Fig. 4-2(a) can be used for the setup shown in Fig. 4-2(c). Whatever specimen design is used to acquire IFQ data under bolt load transfer conditions, the amount of bolt load transfer should be controlled so that the effect of load transfer on IFQ can be more readily defined.

Comments on test specimens geometry and recommended number of test specimens for acquiring the IFQ data are as follows. If possible, the test specimens should be wide enough to acquire valid crack growth data up to a 1" crack size. The IFQ is estimated using fractographic data in the small crack size region (e.g. AL-AU = 0.01" - 0.05"). However, the large crack size data is very useful for: (1) justifying the candidate EIFSD for applications in large crack size region, and (2) developing suitable service crack growth master curves for desired durability analysis conditions. The specimen cross section and pin-to-pin length should provide a stable specimen under applicable compressive loads in the spectrum.

If wide test specimens are not practical due to severe time and cost constraints, narrow width specimens will be the second choice, in which case specimens should be tested to failure under spectrum loading. Fractographic data for the small crack size region (e.g., AL-AU = .01" - .05") can be efficiently acquired in this manner. This information can be used to estimate the EIFSD parameters and to justify the candidate EIFSD for durability analysis. However, the biggest drawback is that the crack growth data in the large crack size region are not available.

The number of test specimens used to acquire the IFQ data depends on the cost constraint, desirable confidence level and time schedule. Of course, the more specimens the better confidence in the results. However, as a general guideline the following is recommended. Use 10-30 specimens to acquire the IFQ data for each test condition to be considered.

4.1.2 Testing Guidelines

All fatigue tests for IFQ specimens are recommended to be performed at room temperature in a lab air environment until failure occurs. A test system which automatically shuts off when the specimen in the fixture fails is recommended. This way, fatigue testing can be periodically monitored and new specimens can be loaded for subsequent testing.

If possible, IFQ data should be acquired for replicate specimens at three different stress levels for a given load spectrum. A high, low and intermediate stress level are recommended to acquire the fatigue cracking data base where possible. This type of information is very useful for determining the EIFSD parameters, and it provides a basis for tuning the analytical crack growth program to make durability analysis predictions for different stress levels. Furthermore, this information can be used to establish an empirical relationship for crack growth parameter as a function of stress level, (Eq. 3-32).

We recommend that all specimens be tested to failure to assure as much uniformity as possible in the crack growth results (i.e., acquire fractographic data that cover a specified AL-AU range). If fatigue testing is stopped at a specified time rather than at specimen failure, the resulting fatigue cracks in the fastener holes may be too small to reliably read the fractographic data. Likewise, if the specimen is not tested to failure, the resulting fatigue crack, if present, may not be obvious, thus, the specimen must be broken open to reveal the fracture surface(s). This requires careful specimen preparation to avoid possible damage to the fracture surface. When the specimen is tested to failure, on the other hand, a "clean" fracture surface results.

4.1.3 Fractographic Data Guidelines

The minimum fractographic crack size to be read should, if possible, correspond to the crack size lower limit, AL, to be used to define the IFQ. For example, AL = 0.01" is recommended. If possible, the fractography should be read to cover the selected AL-AU range for defining the IFQ (e.g., AL-AU = .01" - .05"). When the fractographic data acquired does not cover the selected AL-AU range, TTCIs for a selected reference crack crack size, a_0, may have to be extrapolated. "Mixing and matching" TTCIs based on extrapolations and interpolations should be avoided where possible, because extrapolated values cannot be verified and neither can the contribution to the total variance of the data base.

Use automated crack monitoring techniques as much as possible to minimize fractographic acquisition costs. Also, automatic storing of the fractographic results directly into the computer can minimize the time and costs for plotting results and for estimating the EIFSD parameters.

4.1.4 Utilization of Existing Fractographic Data

Existing fractographic data should be utilized where possible to estimate the IFQ. In some cases, test specimens may contain multiple fastener holes but fractographic results may be available for only the largest fatigue crack per specimen. In other cases, test specimen may have only a single fastener hole. Furthermore, it may be necessary to utilize fractographic data from different sources to estimate the IFQ. In this connection, the statistical scaling procedure described in Section 3.3.4 and elsewhere [2,3] can be used to normalize the fractographic results to a single hole basis.

Fractographic data used to define the IFQ should first be screened and censored for data anomalies such as crack growth data extremes (e.g., very fast or very slow compared to most results in data sets). Software is available in Volume V [24] for efficiently plotting and displaying the fractographic data for desired crack size ranges. This software can be implemented on an IBM or IBM-compatible personal computer. Screening and censoring is essential to assure that the data is reasonably homogeneous and it covers the selected AL-AU range to be used to define the IFQ. "Data sparsity" results when a given fatigue crack has little or no data in the desired AL-AU crack size range.

The fractographic data base should reflect only those fatigue cracks which originate in the bore of the fastener hole. All surface fatigue cracks should be excluded because these are not typical of the fatigue cracking process to be modeled.

4.2 DETERMINATION OF SUITABLE EIFSD

The following guidelines apply to the determination of a suitable EIFSD for durability analysis.

1. The EIFS upper bound limit, x_u, has the following constraint: largest EIFS in any data set $\leq x_u \leq 0.05"$. In general, an x_u value between 0.03" and 0.05" is recommended. The maximum x_u of 0.05" is set by NDI considerations, current damage tolerance initial flaw size requirements and the economical repair limit for fastener holes. If $x_u > 0.05"$ is allowed, this means that the probability of exceeding the economical repair limit will be greater than zero at time zero. This may not be a realistic condition for newly manufactured fastener holes.

2. A fractographic crack size range, AL-AU = 0.01" - 0.05" is recommended for determining the IFQ. Other crack size ranges could also be used. Whatever AL-AU limits are used, the pooled Q value for each data set should be determined from the same AL-AU range. Ideally, the fractographic data should cover the selected AL-AU range.

3. For AL-AU = 0.01" - 0.05", a crack size of 0.05" for TTCIs and a reference crack size of $a_0 = 0.05"$ are considered reasonable. In any case, we recommend the following limits for defining a_0: $AL \leq a_0 \leq AU$.

4. We recommend that the parameters for the Weibull-compatible distribution function (i.e., α, ϕ and x_u) be estimated using the "EIFS fit", the combined least square sums approach (CLSSA), data pooling and statistical scaling procedure [2,3]. It has been shown that the same EIFSD parameter values can be obtained using either the "EIFS fit" or the "TTCI fit" when the CLSSA is used [3].

5. While values of α and ϕ depend upon x_u, we have found, in general, that comparable predictions for $p(i, \tau)$ and/or $F_{T(x_1)}(t)$ can be obtained using different x_u values

and the corresponding α and ϕ . This is due to the fact that α and ϕ are obtained for a given x_u using the least square fit procedure.

6. The Weibull compatible EIFSD function given in Eq. (3-1) is recommended for defining IFQ. Other distribution functions could also be used for this purpose. In any case, a compatible type EIFSD is recommended for defining IFQ because such a distribution imposes physically meaningful limits on TTCIs and EIFSs. For example, all TTCIs are non-negative quantities with values ≥ 0 and the maximum EIFS allowed is governed by x_u. The lognormal compatible is considered to be another reasonable EIFSD function.

7. The methods developed for determining the IFQ of fastener holes has been evaluated for both straight-bore and countersunk clearance-fit fastener holes. Further research is needed to account for the effects of hole life-enhancement features, such as cold working, interference fit fastener, press-fit bushings, etc. on IFQ.

8. The candidate EIFSD should be justified for the planned durability analysis. As a minimum, the candidate EIFSD should be grown forward using the applicable EIFS master curve for each data set to predict: (1) $p(i,\tau)$ at a selected service time, and (2) $F_{T(x_1)}(t)$ at $x_1 = a_0$. Predictions should be correlated with the ranked results for crack size and TTCI, respectively. Software is available in Volume V [24] for testing the candidate EIFSD. Other fractographic data sets not included in the determination of the EIFSD parameters could also be used to test the candidate EIFSD in the small and large crack size regions. If reasonable correlations are obtained for the candidate EIFSD in the manner described above, the EIFSD may be justified for further durability analysis (e.g., same type of load spectrum (fighter, bomber or transport), different stress levels and % bolt load

transfer). An EIFSD is unacceptable if reasonable correlation cannot be obtained in the areas of most interest, when the EIFSD is grown forward.

4.3 ESTIMATION OF STANDARD DEVIATION σ_z

The standard deviation, σ_z, of the log crack growth rate in the large crack size region is needed to implement the two-segment DCGA-SCGA described in Section 3.4. If suitable fractographic results are available, σ_z can be determined using Eq. (3-36) as described in Section 3.5.2, otherwise σ_z will have to be assumed. Ranges of σ_z value are shown in Table 4-1 for both countersunk and straight-bore fastener holes. These results are based on extensive fractographic data evaluations for 7474-T7351 aluminum with clearance-fit fastener holes. The results in Table 4-1 reflect the natural log base and provide information for a reasonable assumption for σ_z value.

4.4 SERVICE CRACK GROWTH MASTER CURVE

A service crack growth master curve (SCGMC) for each stress region is needed to grow the EIFSD forward to predict $p(i,\tau)$ at a given service time, τ, or $F_{T(x_1)}(t)$ for a given crack size x_1. Recommended procedures and guidelines are presented in the following for determining a suitable SCGMC for the small and large crack size regions.

4.4.1 Small Crack Size Region

A SCGMC is needed for the small crack size region (e.g. $a(t) \leq 0.05"$) to evaluate functional impairment due to excessive cracking. In most durability design situations, a suitable LEFM analytical crack growth program [e.g., 31,32] is

Table 4-1 σ_z Ranges for 7475-T7351 Aluminum for Straight-Bore and Countersunk Fastener Holes.

Type Hole	σ_z range(3)
SB(1)	.177 - .271
CSK(2)	.224 - .441

Notes: (1) Straight-bore fastener hole (clearance-fit)

(2) Countersunk fastener hole (clearance-fit)

(3) AL-AU = 0.05" - 2"

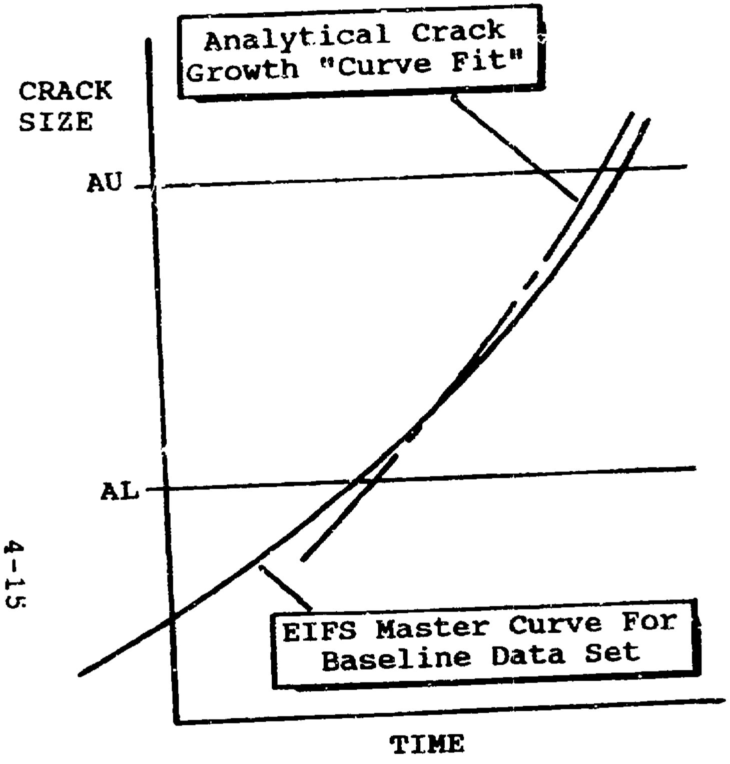
(4) Ref. Volume II [3]

used to develop the SCGMC for the desired analysis conditions because applicable fractographic results may not be available. The following general procedure for developing a SCGMC is recommended for durability analysis applications in the small crack size region.

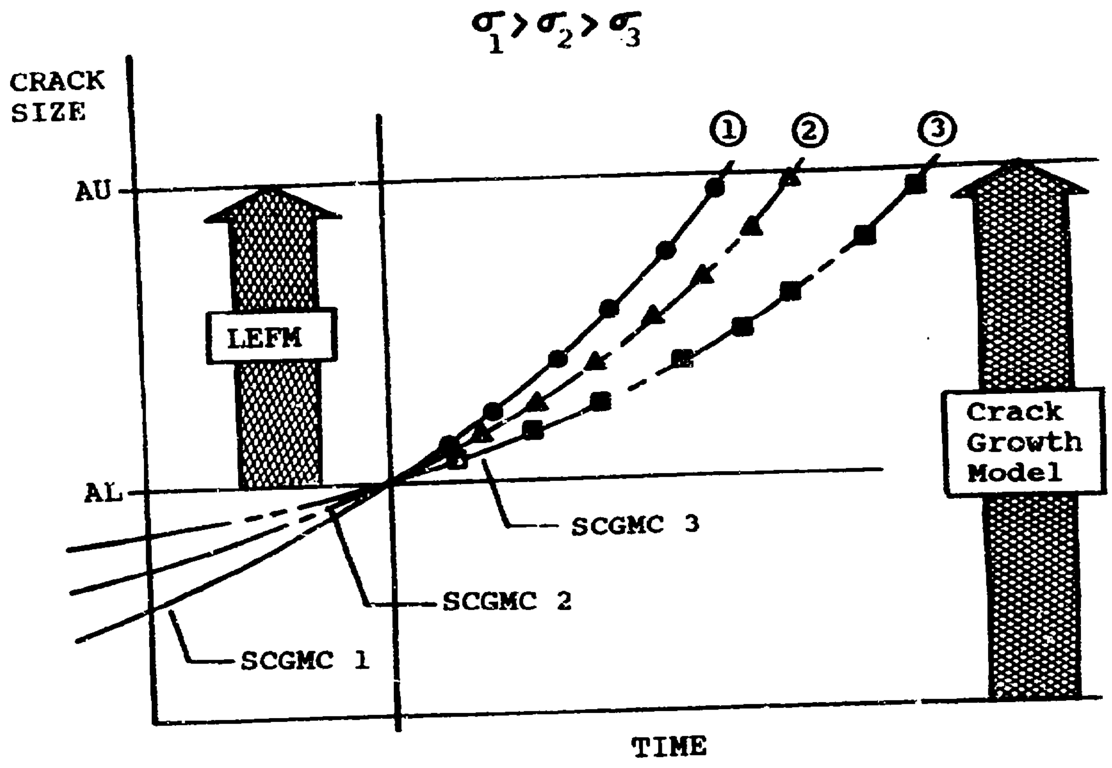
1. Define the bases for the EIFSD to be used in the durability analysis and for EIFS master curve. For example: (1) what fractographic crack size range, AL-AU, was used?; and (2) what method was used to define the EIFS master curve, including criterion for goodness-of-fit and crack shape?

Note: An empirical EIFS-Service time relationship (e.g., Eq. (3-4)) is recommended for general applications so that consistent EIFSs will be obtained by different aerospace contractors for the same fractographic data base.

2. Use a suitable analytical crack growth program to "curve fit" or "tune to" the EIFS master curve or curves in the fractographic crack size range, AL-AU. The "curve fit" to the EIFS master curve in the selected AL-AU range is accomplished using the applicable conditions reflected in the EIFS master curve (i.e., load spectrum, stress level, % bolt load transfer, hole type/diameter). The procedures are given as follows: (1) plot the EIFS master curve to cover the applicable AL-AU range; (2) select a crack growth model (e.g., Walker-ΔK, Forman, etc.); (3) select da/dN versus ΔK data and calibrate the crack growth model parameters for given material; (4) select a load-retardation model (e.g., modified Willenborg, Wheeler, etc.); and (5) by trial and error, determine the remaining model parameters required to obtain a reasonable curve fit (to the EIFS master curve in the AL-AU range) using the analytical crack growth program. The goodness-of-fit is determined subjectively. The above procedure is conceptually described in Fig. 4-3(a).



(a) Tune ("Curve Fit") the analytical crack growth Program to the EIFS master curve for the baseline case in the AL-AU range



(b) Predict a(t) vs t in AL-AU range using tuned crack growth program; obtain SCGMC for each condition using crack growth Model

Figure 4-3. Concept for Determining SCGMC Using Analytical Crack Growth Program and Crack Growth Model.

3. The tuned analytical crack growth program is then used to predict the crack growth over the applicable AL-AU range using the applicable durability analysis conditions. For example, a specific spectrum, stress level and % bolt load transfer and assumed crack shape/geometry are used to predict the crack size at a given time. This step is conceptually illustrated in Fig. 4-3(b) for three different stress levels ($\sigma_1 > \sigma_2 > \sigma_3$). The crack size-time predictions in the AL-AU range are indicated in Fig. 4-3. The analytical crack growth program is used further to make crack size-time predictions for crack size greater than AU where LEFM principles apply. Procedures and assumptions for the analytical crack growth analysis are the same as those used for a typical damage tolerance analysis.

4. Estimate Q_1 in Eq. (3-16) using the predicted crack size-time predictions (i.e., a(t) versus t) in the AL-AU range for a given stress region, depicted in Fig. 4-3(b). Methods for estimating "Q_1" are given in Section III. As shown in Fig. 4-3(b), LEFM principles are used only for the crack size range where such principles apply.

4.4.2 Large Crack Size Region

For the two-segment DCGA-SCGA, the first segment covers the small crack size range (i.e., $a(t) \leq a_0$) and the second segment covers the large crack size range, $a(t) > a_0$, as shown in Fig. 4-4. The first segment was obtained previously whereas the second segment can be determined as follows.

The tuned analytical crack growth program obtained above is used to predict the crack growth (i.e., a(t) versus t) from a_0 = AU to AU$'$ for the desired analysis conditions (i.e., stress level, load spectrum, % bolt load transfer, etc.). For example, such crack growth predictions are shown

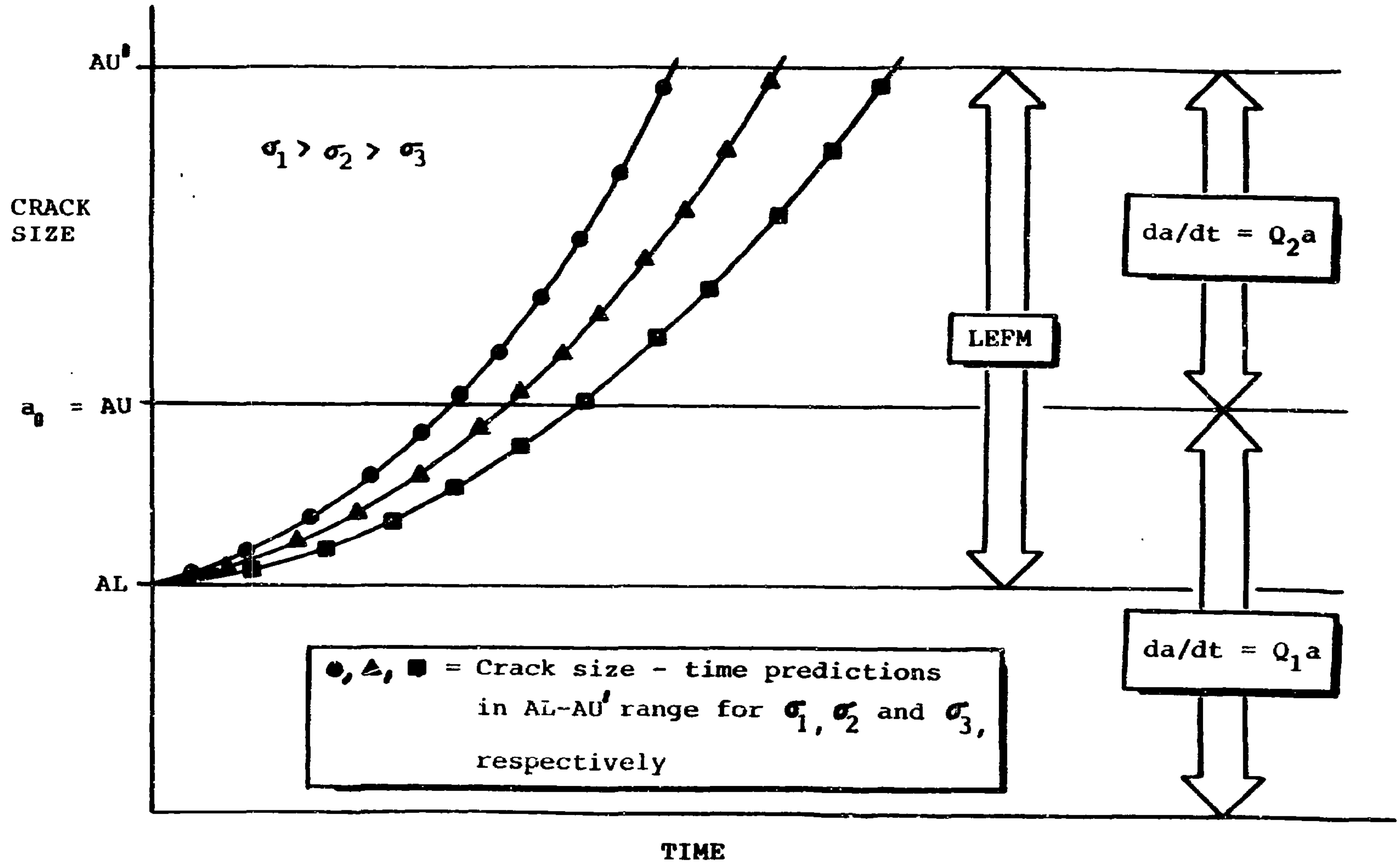


Figure 4-4. Use of Analytical Crack Growth Predictions and Crack Growth Model to Establish SCGMCs for Durability Analysis Extension.

in Fig. 4-4 for three different stress levels, in which $\sigma_1 > \sigma_2 > \sigma_3$. In Fig. 4-4 the analytical crack growth predictions cover a crack size range where LEFM principles apply (i.e., $a(t) \geq a_0 = AU$). The crack growth rate parameter Q_2 for the second segment of SCGMC in Eq. (3-17) can be estimated similarly.

The two crack growth master curve segments for a given stress level can be physically combined into a single SCGMC as illustrated in Fig. 4-5. At point i segments 1 and 2 have the same (a(t), t) values but not necessarily the same slopes.

The two-segment SCGMC for the DCGA-DCGA can also be used for the DCGA-SCGA for the same crack growth analysis conditions (e.g., stress level, load spectra, etc.). The only difference is that the parameter σ_z is required to implement the DCGA-SCGA. σ_z is the standard deviation of da/dt with respect to the plot of $\ln da/dt = \ln a(t) + Qt$. σ_z can be determined from suitable fractographic results, if available.

4.5 GUIDELINES FOR SELECTING STRESS REGIONS AND STRESS LEVELS

For durability analysis purposes, a durbility-critical part or component is divided into many stress regions. In each stress region, the stress level at each structural detail is approximately the same. The number of stress regions needed for the durability-critical component depends on the types of structural details to be considered (e.g., fastener holes, cutouts, lugs, fillets, etc.) and the variation of governing stress levels. Different types of structural details cannot be included in the same stress region and they should be separated. Some structural details introduce a higher stress intensity factor and hence a higher crack growth rate.

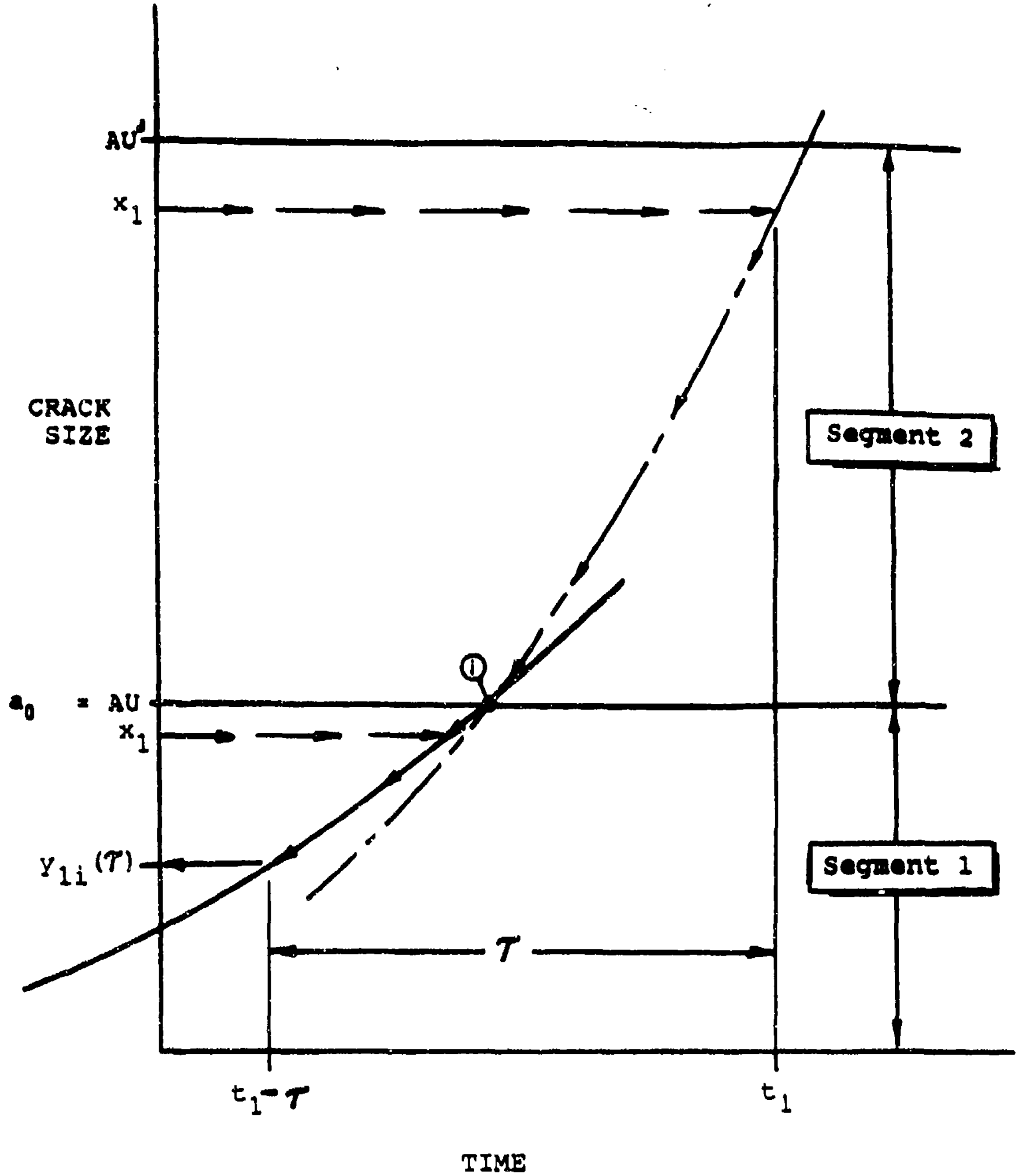


Figure 4-5. Mechanics of Two-Segment SCGMC for Durability Analysis Extension.

Likewise, appropriate finite element grid sizes should be used to achieve the stress analysis accuracy desired. A suitable stress analysis is very important because the governing stress for a given stress region can have a significant influence on the crack growth predictions for the structural details.

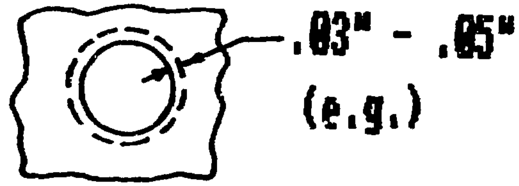
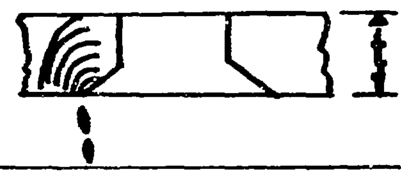
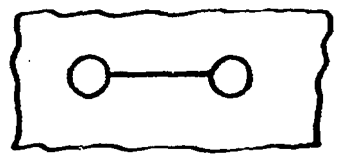
4.6 EXTENT OF DAMAGE GUIDELINES

The durability analysis methodology developed can be used to estimate the extent of damage in a durability-critical component due to excessive cracking, fuel leaks and ligament breakage. The extent of damage depends on the specified crack size limits for functional impairment. For example, typical limits are illustrated in Table 4-2 for fastener holes. Functional impairment crack size limits for other types of structural details are specified by the user.

Structural details in the durability-critical component to be reflected in the durability analysis are divided into stress regions. Functional impairment crack size limits can vary for each stress region and each type of structural detail. The extent of damage for a given exceedance probability can be predicted separately for each type of structural detail in the component (e.g., fastener holes, cutouts, fillets, lugs, etc.) and each type of functional impairment. Also, the overall extent of damage due to different types of structural details can be estimated by combining the extent of damage results for all details in each stress region.

The extent of damage at a given service time for a durability-critical component should be estimated for selected

Table 4-2. Example of Crack Size Limits for Functional Impairment.

FUNCTIONAL IMPAIRMENT	STRUCTURAL DETAIL TYPE	LIMITING CRACK SIZE
Excessive Cracking	Fastener Hole	Economical Repair Limit 
Fuel Leaks	Fastener Hole	Thickness of fuel tank boundary at fastener hole 
Ligament Breakage	Fastener Holes	Hole-To-Hole Edge Dimension 

exceedance probabilities. For example, when the binomial distribution is approximated by the Normal distribution, the average extent of damage corresponds to an exceedance probability of $P = 0.5$. The upper bound limit for the extent of damage could be estimated, for example, at $P = 0.05$. In other words, the probability of exceeding the upper bound limit for the extent of damage in this case would be 5%. Therefore, the statistics, such as the mean and upper bound limit for the extent of damage provides a physically meaningful description of the expected state of structural damage due to fatigue cracking at any service time. This quantitative type of information provides a sound basis for evaluating structural durability requirements and for assessing durability design tradeoffs for metallic durability-critical components.

SECTION V

DEMONSTRATION OF DURABILITY ANALYSIS METHODS

The two-segment deterministic stochastic crack growth approach (DCGA-SCGA) for durability analysis described in Section III and documented in Volume I [2] is demonstrated in this section. Durability analysis methods for predicting the crack exceedance probability, $p(i,\tau)$, and the cumulative distribution of service time to reach any crack size, $F_{T(x_1)}(t)$, are demonstrated using: (1) coupon specimen and (2) the F-16 lower wing skins.

5.1 DEMONSTRATION FOR DOG-BONE SPECIMENS

The advanced durability analysis method described in Section III is demonstrated for both countersunk and straight-bore fastener holes in the following. The initial fatigue quality is established based on fractographic results obtained using narrow specimens. Then, predictions for the crack exceedance probability, $p(i,\tau)$, and cumulative distribution of service time to reach a specific crack size, $F_{T(x_1)}(t)$, in the large crack size region are made using the DCGA-SCGA. Predictions are correlated with actual fractographic results obtained using wide dog-bone specimens.

5.1.1 Countersunk Fastener Holes

The initial fatigue quality of countersunk fastener holes will be determined using the narrow width specimen (Fig. 5-1) test results, i.e., AFXLR4, AFXMR4 and AFXHR4 data sets. Then, the durability analysis prediction will be made for the test results of wide width specimens (Fig. 5-2), i.e., WAFXMR4 and WAFXHR4 data sets where large fatigue cracks exist. Correlations between the theoretical predictions and test results will be made to demonstrate the validity of the durability analysis methodology. The narrow

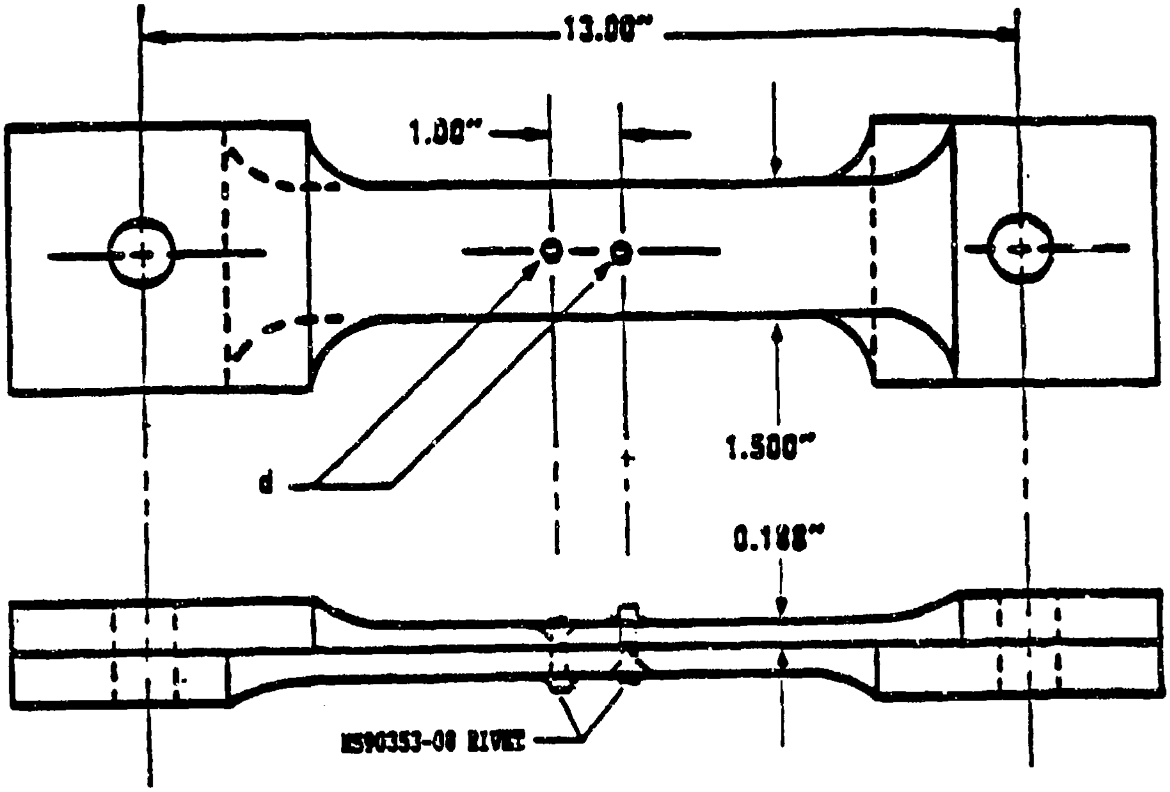
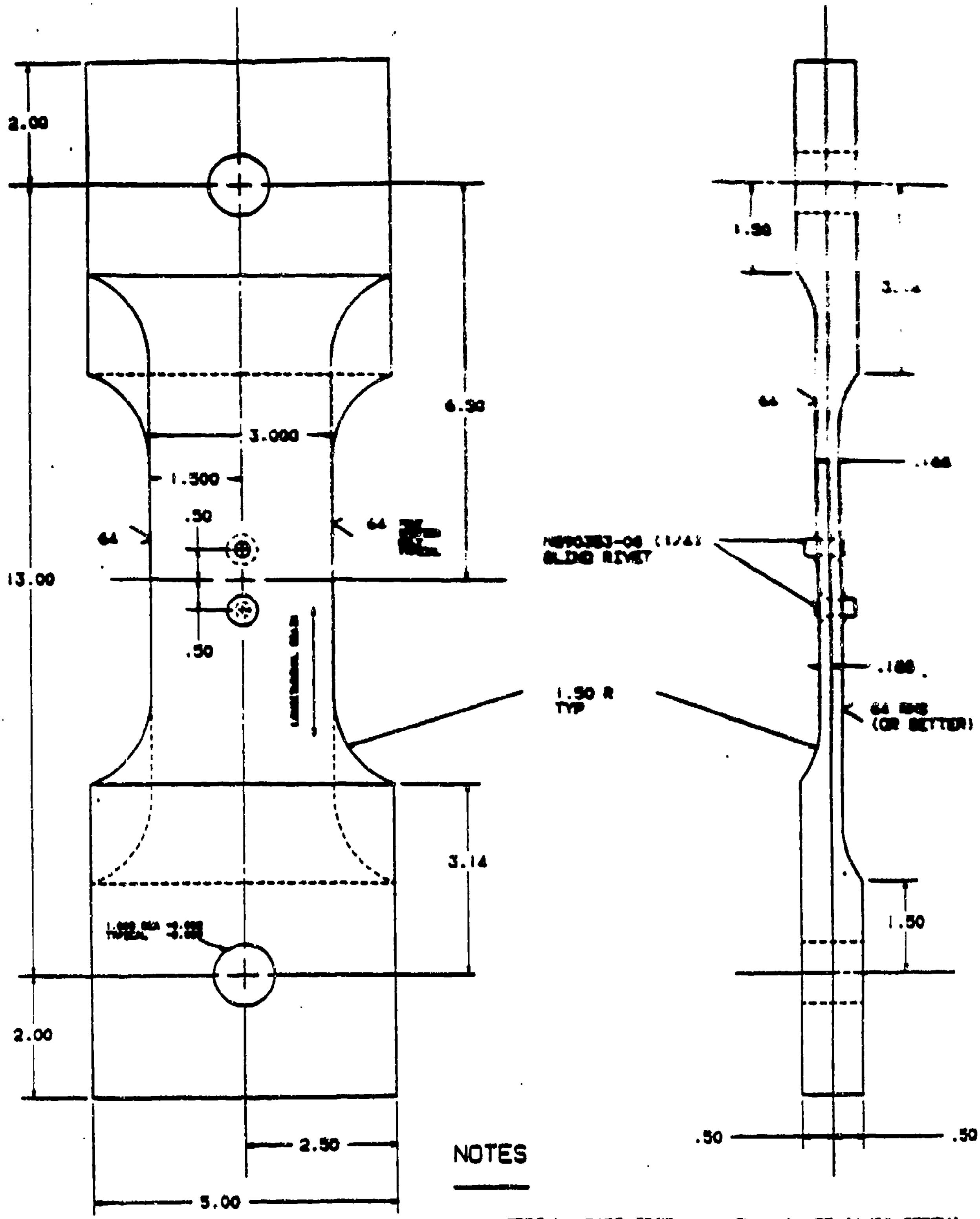


Figure 5-1. Narrow 15% Bolt Load Transfer Specimen Design (W = 1.5").



NOTES

1. MATERIAL: 7475-T7351 ALUMINUM PLATE (1/2" STOCK)

2. MATCH DRILL HOLES USING MODIFIED WINSLOW SCHEMATIC DRILL (NO DEBURRING)

3. DRILL AND INSTALL NS90353-08 RIVETS PER NI98

Figure 5-2. Wide 15% Bolt Load Transfer Specimen Design (W = 3.0").

(W = 1.50") and wide (W = 3.00") width data sets used are described in Tables 5-1 and 5-2, respectively.

The procedures used in the demonstration are given as follows:

1. Use the Weibull compatible distribution function and the pooled data sets (i.e., AFXLR4, AFXMR4 and AFXHR4) in Section 3.3.1 of Volume II [3] to define the IFQ of countersunk fastener holes in 7475-T7351 aluminum. The following EIFSD parameters are obtained: x_u = 0.03", α = 1.716 and ϕ = 6.308 (see Table 5-3).

2. Determine the crack growth rate parameter Q_1 for WAFXMR4 and WAFXHR4 data sets in the small crack size region, (i.e., AL-AU = 0.01" - 0.05"), using the pooled Q values from AFXMR4 and AFXHR4 data sets, respectively. Determine the crack growth rate parameter Q_2 and the corresponding standard deviation σ_z for WAFXMR4 and WAFXHR4 data sets in the large crack size region (i.e., a_0-AU' = 0.05"-0.5") using the fractographic results of WAFXMR4 and WAFXHR4 data sets, respectively.

3. Use the DCGA-SCGA to predict the crack exceedance probability $p(i,\tau)$ in the large crack size region and the distribution of service time $F_{T(x_1)}(t)$ to reach a specific large crack size x_1.

4. Correlate analytical predictions with the actual test results for two wide specimen data sets; i.e., WAFXMR4 and WAFXHR4.

WAFXMR4 and WAFXHR4 data sets were tested using the F-16 400 hour spectrum with a maximum peak gross stress of 34 ksi and 40.8 ksi, respectively. The "F-16 400 hour spectrum" has been used extensively in recent years in General Dynamics'

Table 5-1. **Description of Fractographic Data Sets Used to Determine the IFQ for Countersunk Fastener Holes.**

DATA SET (Ref. 25)	SPECIMENS USED (4)	σ (3) (ksi)	LT (%)	WIDTH (In.)	t (In.)	FASTENER (2)	LOAD SPECTRUM
AFXLR4	10/11 (5)	32	15	1.5	.1875	MS90353-08	F-16 400 HR
AFXMR4	9/9	34					
AFXHR4	10/10	38					

Notes: (1) Material: 7475-T7351 aluminum
(2) Blind pull-through rivet (countersunk head)
(3) Gross section stress
(4) xx/yy = No. of specimens used/total no. of specimens in data set
(5) Deleted crack no. 8 from data set

Table 5-2. **Description of WAFXMR4 and WAFXHR4 Fractographic Data Sets.**

DATA SET	% LOAD TRANSFER	NO. CRACKS	GROSS STRESS (KSI)	WIDTH (In.)
WAFXMR4	15	14	34	3.0
WAFXHR4	15	13	40.8	3.0

Notes: 1. **7475-T7351 Aluminum**
2. Ref. Fig. 5-2 for specimen design details.
3. Ref. 39

Table 5-3. Summary of IFQ Parameters for Pooled Countersunk Data Sets Based on the Weibull Compatible Distribution Function.

DATA SET	NO. CRACKS	MAX. STRESS (ksi)	ℓ	AL-AU	$Qx10^4$ (1/HR.)	x_u (IN.)	α	ϕ	MEAN EIFS $x10^4$
AFXLR4	10	32	4	.01"-.05"	2.101	.02	1.330	6.704	42.40"
AFXMR4	9	34	4		2.514	.03	1.716	6.308	62.43"
AFXHR4	10	38	4		6.062	.05	2.132	6.453	34.29"

Notes: 1. CLSSA used
2. Used data pooling procedure
3. Ref. 38

IRAD and CRAD research programs. However, this spectrum doesn't apply to F-16 production aircraft. Theoretically, there is no significant difference in the peak stress at the edge of the fastener hole for narrow (W = 1.5") or wide (W = 3.0") specimen subjected to the same gross section stress. The narrow specimen has a slightly larger net section stress than the wide specimen. However, the narrow specimen has a smaller stress concentration factor than the wide specimen. These compensating factors are the reason the maximum peak stress at the edge of the fastener hole is virtually the same for both narrow and wide specimens subjected to the same gross section stress.

5.1.1.1 Estimation of Service Crack Growth Parameters.

EIFSD parameters for countersunk fastener holes based on specimen data sets AFXLR4, AFXMR4, and AFXHR4, are shown in Table 5-3. Pooled Q values for each of these data sets are also shown in Table 5-3.

The crack growth rate parameters Q_1 and Q_2 vary with respect to service loading conditions. However, when all service loading conditions are identical, such as loading spectra, percentage of load transfer, type of fastener holes, etc., except the maximum gross section stress level σ, a very reasonable model relating the crack growth rate parameter Q and the maximum gross section stress is given in Eq. (3-32).

Thus, if fractographic data sets are available under several different gross stress levels, σ_i, the empirical parameters C and V in Eq. (3-32) can be determined using the least square fit procedure. Then, the crack growth rate parameters Q_1 and Q_2 under different gross stress levels can be computed from Eq. (3-32). For demonstrative purpose, since applicable fractographic results in the small crack size region are available for AFXLR4, AFXMR4 and AFXHR4 narrow specimen data sets, Eq. 3-32 is used to determine the crack growth rate parameters Q_1 for WAFXMR4 and WAFXHR4 data sets as well as various stress regions in the lower wing skin of the F-16 aircraft.

In the small crack size region of AL-AU = 0.01" - 0.05", Q values versus gross stresses for the AFXLR4, AFXMR4 and AFXHR4 data sets shown in Table 5-3 are plotted in Fig. 5-3 as solid circles. Using the model of Eq. (3-32) and a least-squares-fit procedure, a straight line is obtained in Fig. 5-3; with C = 4.829×10^{-4} and V = 6.38. With the values of C and V given above as well as the gross stresses for WAFXMR4 and WAFXHR4 data set, Q_1 values for these two data sets are computed from Eq. (3-32) as 2.851×10^{-4} per hour and 9.126×10^{-4} per hour, respectively.

Fractographic results available in the large crack size range, i.e., a_0-AU' = 0.05" - 0.5", for AFXLR4, AFXMR4 and AFXHR4 data sets are not sufficient to determine the respective pooled Q_2 values, because the specimens for these data sets are only 1.5" wide. As a result, the crack growth rate parameters Q_2 and the corresponding standard deviation σ_z for egment 2, i.e., a_0-AU' = 0.05" - 0.5", for WAFXMR4 and WAFXHR4 were determined using the fractographic results of these two data sets. Q_2 and σ_z values for WAFXMR4 and WAFXHR4 are summarized in Table 5-4 in which the value of Q_2 is denoted as Q.

5.1.1.2 Theoretical/Experimental Correlations. Theoretical predictions for the probability of crack exceedance $p(i, \tau)$, and the cumulative distribution of time to reach a given crack size $F_{T(x_1)}(t)$, for the WAFXMR4 and WAFXHR4 data sets have been computed using the DCGA-SCGA. All results are based on the following EIFSD parameters for the Weibull compatible distribution function: x_u = 0.03", α = 1.716, ϕ = 6.308 (see Table 5-3).

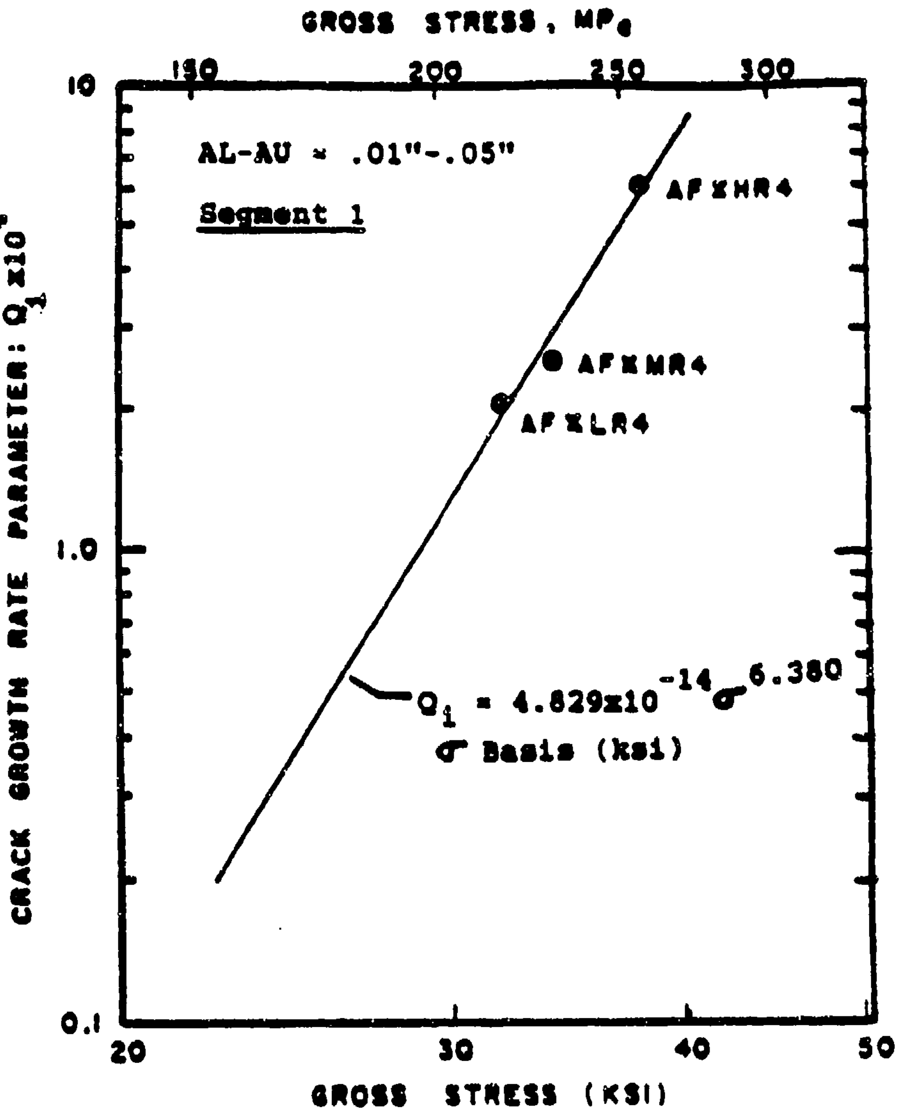


Figure 5-3. Crack Growth Rate Parameter Q Versus Gross Stress for Narrow Specimen Data Sets (AFXLR4, AFXMR4, AFXHR4).

Table 5-4. Summary of Q and σ_z for WAFXMR4 and WAFXHR4 Data Sets

DATA SET (1)	% LT	NO. CRACKS	MAX. STRESS (ksi)	WIDTH (In.)	a_0 - AU'	Q x10^4 (1/Hr.)	σ_z (2)
WAFXMR4	15	14	34	3.00	0.05"-.5"	2.906	0.449
WAFXHR4	15	13	40.8	3.00	0.05"-.5"	3.854	0.322

Notes: (1) Ref. Fig. 5-2 for specimen design details (7475-T7351 aluminum)
(2) Ref. Eq. (3-36)(Natural log basis)

The predicted probability of crack exceedance at τ = 11,608 flight hours for WAFXMR4 is displayed in Fig. 5-4 as a solid curve. Also shown in this figure as solid circles are the actual test data for comparison. Further, the predicted probability of crack exceedance at τ = 7,000 flight hours for WAFXHR4 is shown in Fig. 5-5 as a solid curve and the solid circles denote the actual fractographic test results.

The predicted cumulative distribution of service time to reach a crack size of 0.73" for the WAFXMR4 data set is displayed in Fig. 5-6 as a solid curve. The actual fractographic results are shown in the same figure as solid circles for comparison. Similarly, the prediction for the cumulative distribution of service time to reach a crack size of 0.59" for WAFXHR4 is shown in Fig. 5-7 as a solid curve. The solid circles depicted in the same figure are the actual fractographic test data for comparison. It is observed from Figs. 5-4 to 5-7 that the correlations for countersunk fastener holes between the experimental results and the durability analysis predictions are very reasonable.

5.1.2 Straight-Bore Fastener Holes

The DCGA-SCGA for durability analysis is demonstrated for straight-bore clearance-fit fastener holes in 7475-T7357 aluminum in this section. Procedures for the demonstration are given as follows.

1. The IFQ for straight-bore clearance-fit fastener holes is based on the Weibull-compatible EIFSD. Two narrow width (W = 1.5") specimen data sets (WPF and XWPF; see Figs. 5-8 and 5-9, and Table 5-5), a data pooling procedure and a statistical scaling technique [2] were used to estimate the EIFSD parameters α and ϕ for x_u = .03". Results are summarized in Table 5-6.

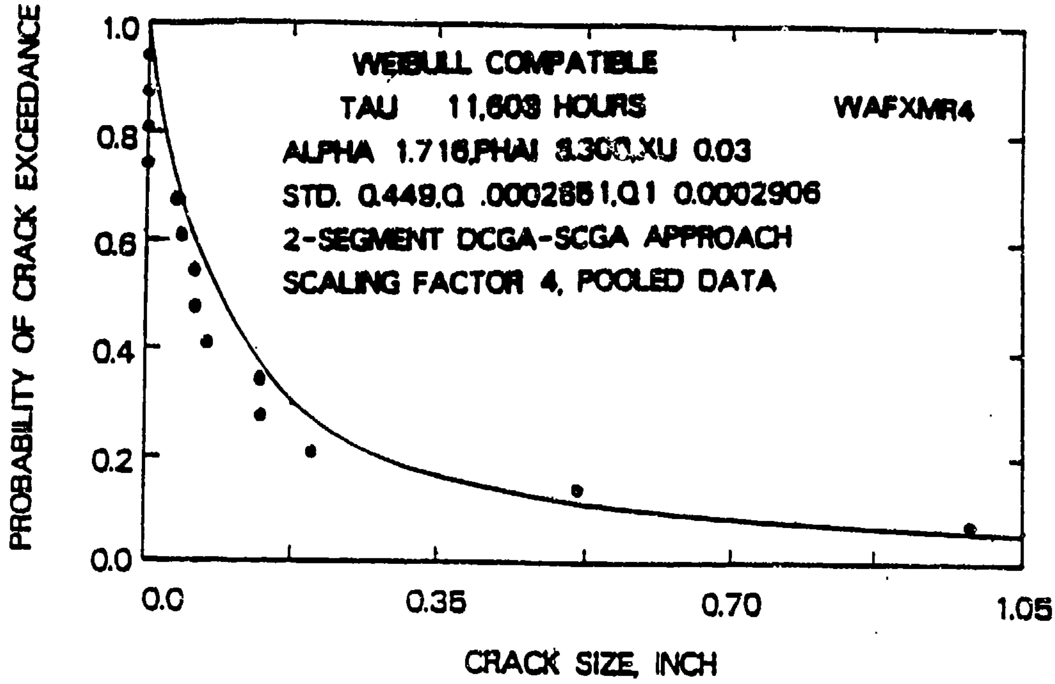


Figure 5-4. <u>Correlation Between Predicted Crack Exceedance Probability at τ = 11608 Flight Hours for WAFXMR4 Data Set and Actual Fractographic Results</u>.

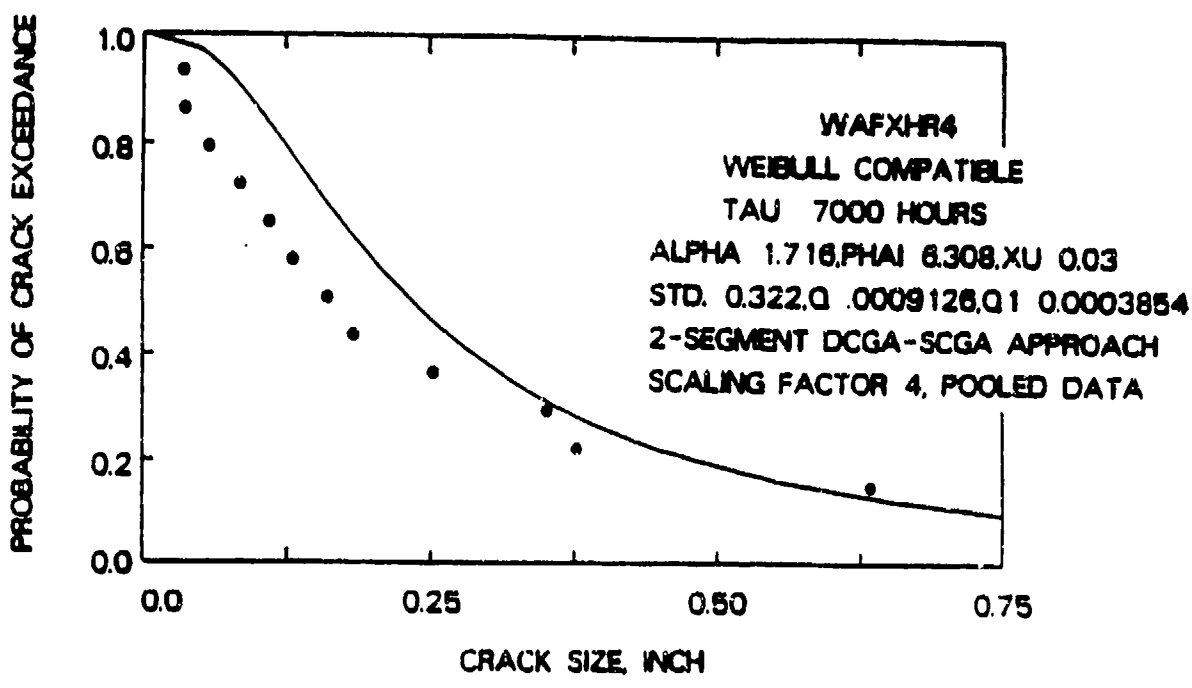


Figure 5-5. <u>Correlation Between Predicted Crack Exceedance Probability at τ = 7000 Flight Hours for WAFXHR4 Data Set and Actual Fractographic Results</u>.

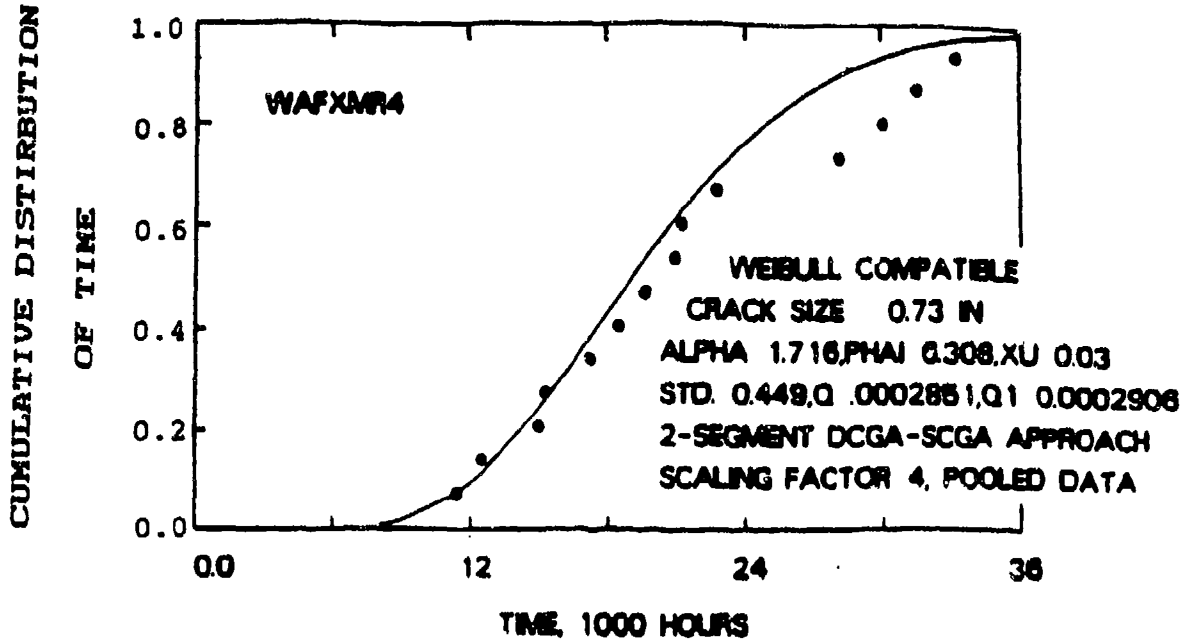


Figure 5-6. <u>Correlation Between Predicted Distribution of Service Time to Reach 0.73" Crack Size for WAFXMR4 Data Set and Actual Fractographic Results.</u>

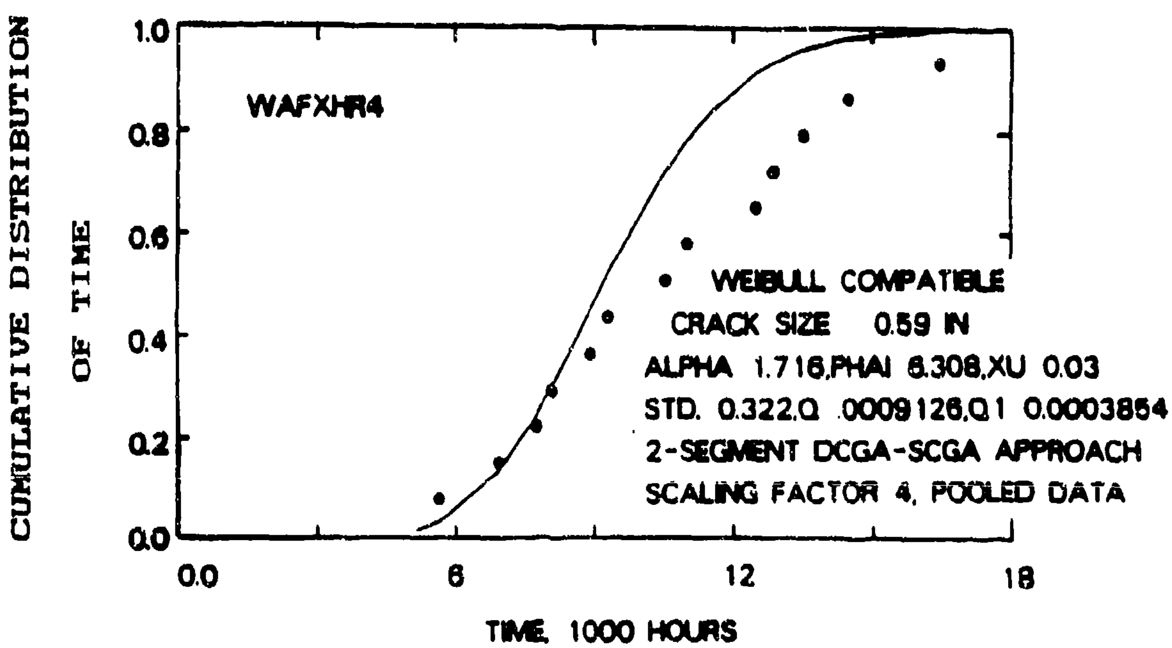


Figure 5-7. <u>Correlation Between Predicted Distribution of Service Time to Reach 0.59" Crack Size for WAFXHR4 Data Set and Actual Fractographic Results.</u>

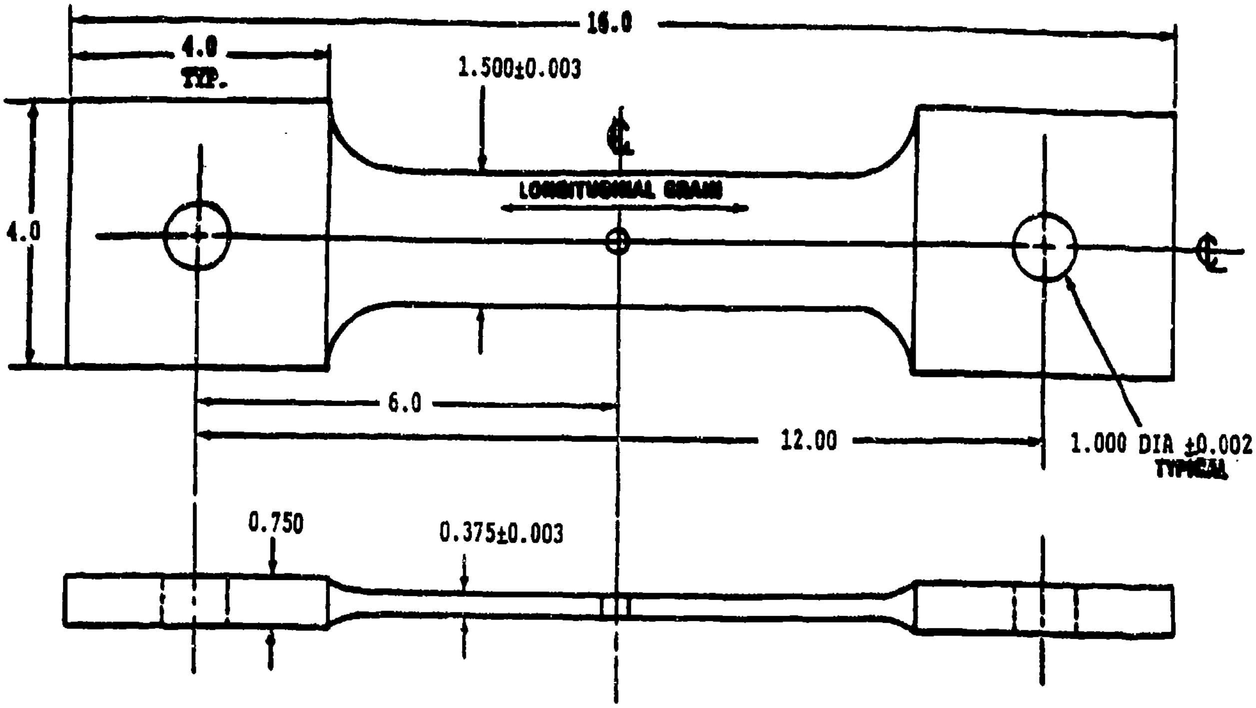


Figure 5-8. **Dog-Bone Specimen with 1.5" Width.**

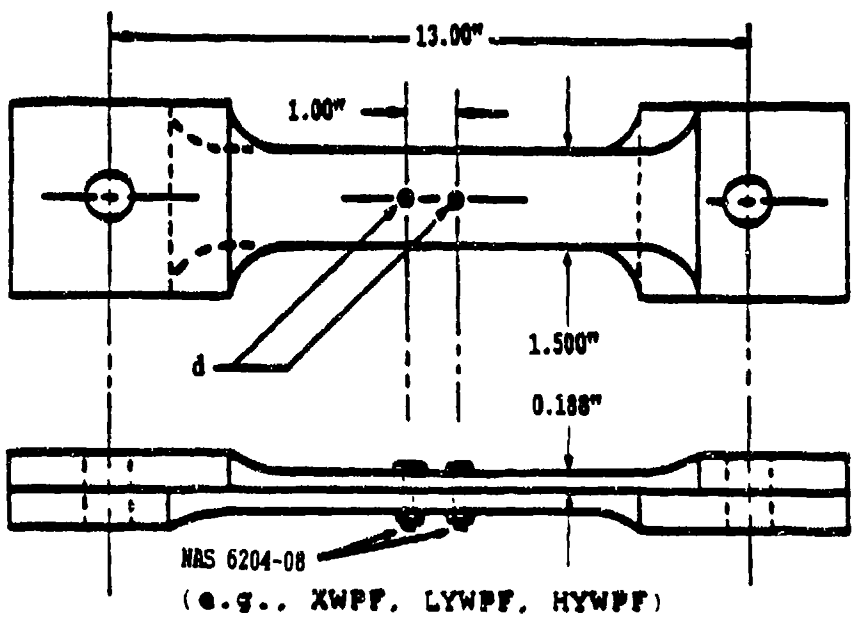


Figure 5-9. **Double-Reversed Dog-Bone Specimen with 1.5" Width.**

Table 5-5. **Description of Fractographic Data Sets Used to Determine the IFQ for Straight-Bore Fastener Holes.**

Data Set (1)	No. of Specimens Used	(4) (KSI)	% LT	W (In.)	Fastener	Load Spectrum
WPF (5)	31/33 (2)	34	0	1.5	NAS6204-8	F-16 400 HR
XWPF	31/33 (3)	34	15	1.5	↓	↓

Notes:
(1) 7475-T7351 Aluminum
(2) Deleted fatigue cracks #2 and 6
(3) Deleted fatigue cracks #11 and 16
(4) Gross section stress for peak spectrum load
(5) Ref. FHQ program [37]

Table 5-6. Summary of IFQ Parameters for Pooled Straight-Bore Hole Data Sets Based on Weibull Compatible Distribution Function

DATA SET (1)	NO. SPECIMENS	AL - AU	Q $\times 10^4$ (1/Hr.)	x_u	α	ϕ	ℓ
WPF	31/33	0.01"-0.05"	2.329	0.03"	4.782	4.658	1
XWPF	31/33		3.671				4

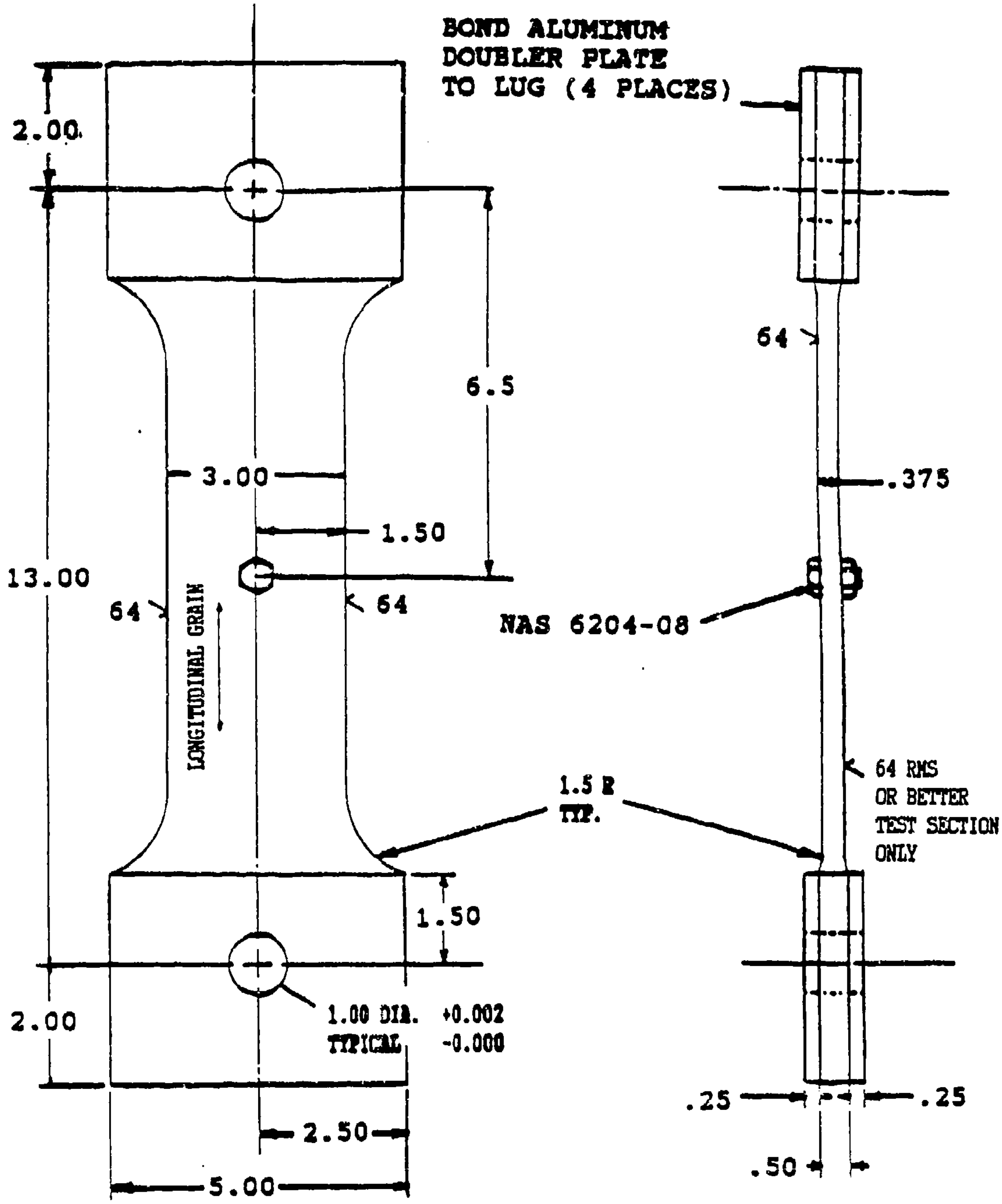
Notes: (1) Ref. 37
(2) CLSSA and "EIFS fit" used

2. The crack growth rate model of Eqs.(3-16) and (3-17) (with $b_1 = b_2 = 1$) and fractographic data for the WWPF data set are used to estimate the crack growth parameter Q_1 and Q_2 respectively. Specimen design details for the WWPF data set, shown in Fig. 5-10, are the same as the WPF data set in the test section, except that the WWPF specimen is wider (i.e., 3.0" width). Such specimens are wide enough to provide fractographic data in the large crack size region. Specimens for the WWPF data set were fatigue tested to failure using the same load spectrum (F-16 400 hour) and maximum peak (gross) stress level (i.e., 34 ksi) as the "WPF" data set. In the present demonstrations, AL-AU = 0.01" - 0.05" is used for the small crack size region (i.e., "Segment 1") and a_0-AU$'$ = 0.05" - 1" is used for the large crack size region (i.e., "Segment 2"). Results for Q_1, Q_2 and σ_z for the WWPF data set are summarized in Table 5-7.

3. Theoretical predictions for the probability of crack exceedance, $p(i, \tau)$, at service time $\tau = 18{,}400$ flight hours, are shown in Fig. 5-11 for the DCGA-SCGA. Experimental results are denoted as solid circles for comparison.

4. Theoretical predictions for the cumulative distribution of service time to reach a crack size $x_1 =$ are shown in Fig. 5-12 for the DCGA-SCGA. Experimental results for the WWPF data set are plotted as plus signs (+) for comparison.

The theoretical predictions shown in Figs. 5-11 and 5-12 correlate well with actual test results for both the small and large crack size regions. Hence, the DCGA-SCGA for durability analysis can be used to assess functional impairment due to excessive cracking, fuel leaks and/or ligament breakage.



NOTES: 1. MATERIAL: 7475-T7351 Aluminum Plate (1/2" STOCK)
2. Drill holes using modified Winslow Spacematic (no deburring)
3. Drill and install NAS 6204-08 bolt per M198
4. All dimensions in inches

Figure 5-10. Dog-Bone Specimen with 3.0" Width.

Table 5-7. Summary of Q and σ_z Values for WWPF Data Set.

DATA SET (1)	NO. SPECIMENS	SEGMENT 1 (3)	SEGMENT 2 (4)	
		$Q_1 \times 10^4$ (1/HR.)	$Q_2 \times 10^4$ (1/HR.)	σ_z
WWPF (2)	13	2.742	3.124	.177

Notes: (1) Material: 7475-T7351 aluminum; straight-bore fastener holes with clearance-fit fasteners (NAS 6204-08)

(2) Ref. Fig. 5-10

(3) AL - AU = 0.01" - 0.05"

(4) a_0 - AU' = 0.05" - 1"

(5) Ref. Eq. 3-36 (Natural log basis)

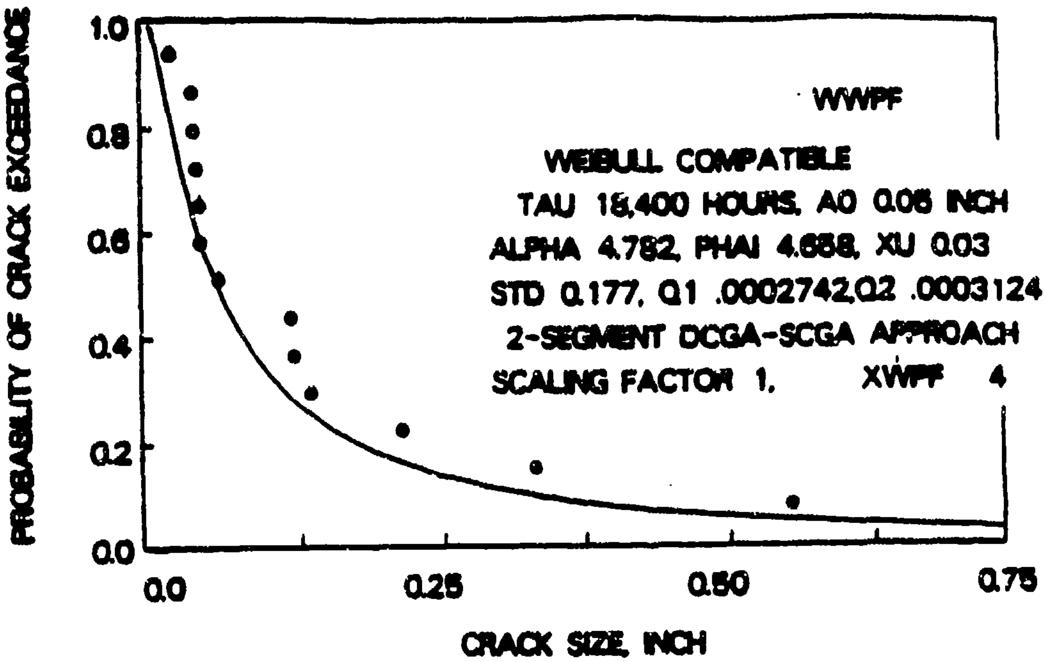


Figure 5-11. Correlation Between Predicted Crack Exceedance Probability Based on the DCGA-SCGA at T = 18,400 Flight Hours for WWPF Data Set and Actual Fractographic Results.

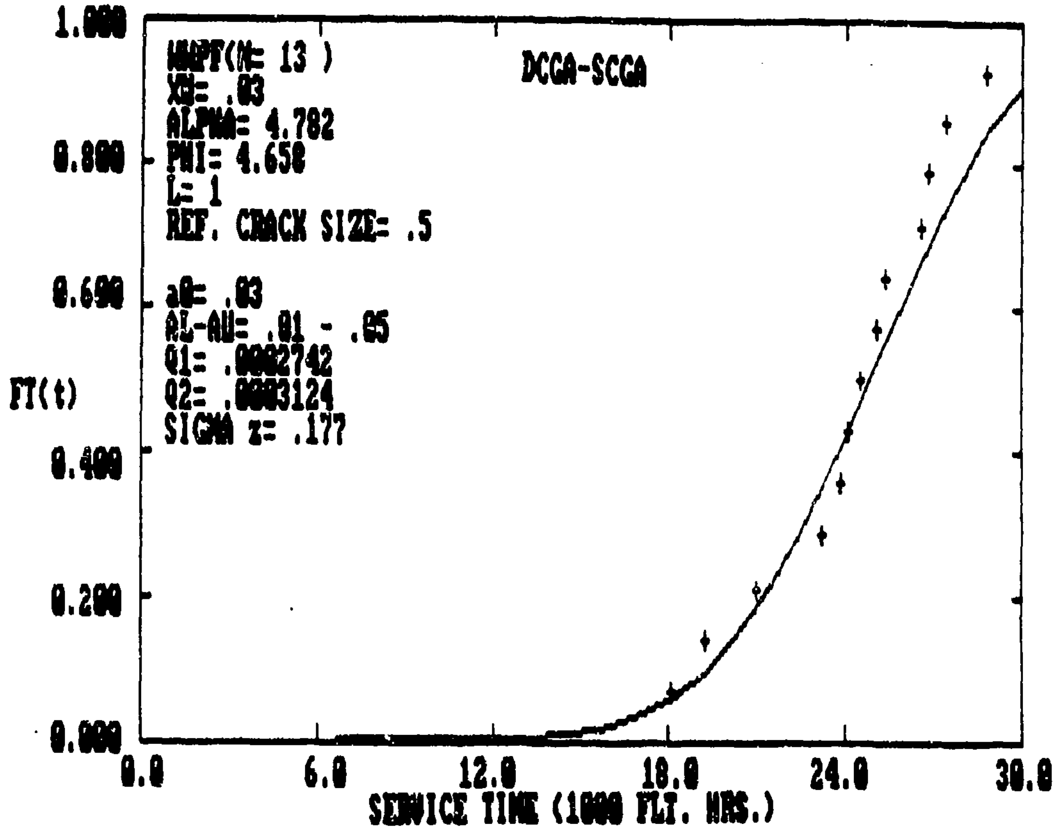


Figure 5-12. <u>Correlations Between Theoretical Predictions and Experimental Results (WWPF Data Set) for Cumulative Distribution of Service Time to Reach Crack Size $x_1 = 0.5''$ Based on DCGA-SCGA.</u>

5.2 DEMONSTRATION FOR THE F-16 LOWER WING SKINS

A durability analysis of the F-16 lower wing skins has been previously reported [1,17,20-22]. This analysis was concerned with relatively small fatigue cracks (e.g., $x_1 \leq$ for excessive cracking and reflected the one-segment DCGA [1,16].

A durability analysis of the F-16 lower wing skin for functional impairment is conducted herein using the two-segment DCGA-SCGA. The two-segment DCGA-SCGA is demonstrated and evaluated in the following and in Volume II [3]. Predictions will be correlated with results from the F-16 wing durability test article. The F-16 wing box assembly is shown in Fig. 5-13 and stress regions for the lower wing skin are shown in Fig. 5-14.

A full-scale F-16 wing durability test was conducted using the F-16 1000 hour spectrum, consisting of two 500 hour blocks. After fatigue testing to 16,000 flight hours, a tear-down inspection was performed. All fastener holes in both lower wing skins (i.e., 3228 holes) were inspected using the eddy current technique. Each fastener hole with a crack indication was broken open and a fractographic analysis was performed. Tear-down inspection and fractographic results are documented in Ref. 38.

The following procedures are used to demonstrate and evaluate the two-segment DCGA-SCGA using the F-16 lower wing skins for the durability analysis for functional impairment associated with large through-the-thickness cracks.

1. The IFQ is based on the fractographic results from AFXLR4, AFXMR4 and AFXHR4 data sets. The EIFSD parameters, based on the fractographic data in the small crack size range AL-AU = 0.01" - 0.05" and $\ell = 4$ for each of the three data sets have been obtained in the previous example to define the

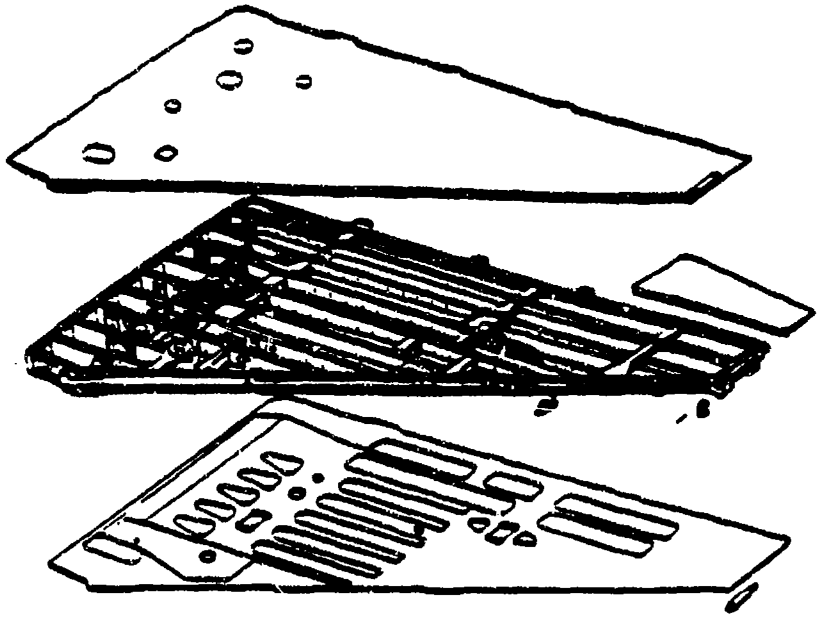


Figure 5-13. **F-16 Wing Box Assembly.**

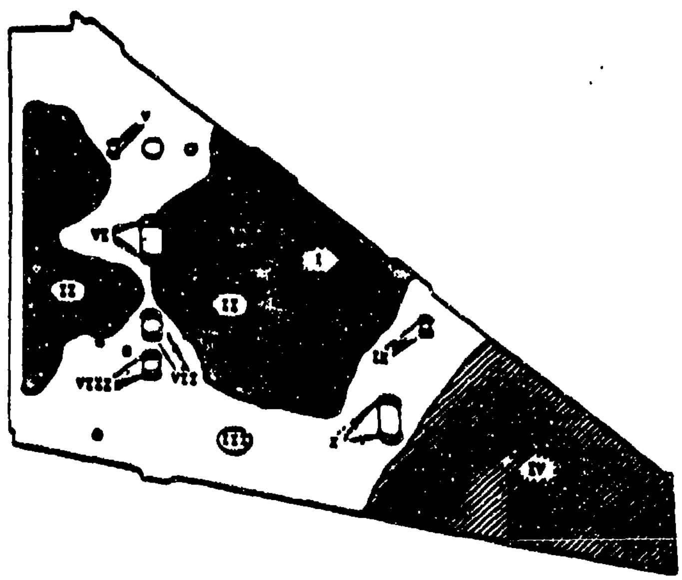


Figure 5-14. **Stress Regions for F-16 Lower Wing Skin.**

IFQ of countersunk fastener holes; with the results x_u = 0.03", α = 1.716 and ϕ = 6.308, see Table 5-3.

2. The F-16 lower wing skin is divided into 10 stress regions as shown in Fig. 5-14. The stress level and the number of fastener holes in each stress region are shown in Table 5-8.

3. The crack growth rate parameter, Q_1 for segment 1, in each stress region are determined using: (i) the available pooled Q values from the AFXLR4, AFXMR4 and AFXHR4 data sets (see Table 5-2; AL-AU = 0.01"-0.05"), and (ii) the model for Q as a function of stress given by Eq. (3-32). Results of the model parameters C and V in Eq. (3-32) obtained from three data sets (AFXLR4, AFXMR4 and AFXHR4) have been computed in the previous example, Fig. 5-3, and they are shown in Fig. 5-15, Frame A.

4. The crack growth rate parameters, Q_2, for Segment 2 in each stress region are determined using available wide specimen fractographic results from WAFXMR4 and WAFXHR4 data sets in a_0-AU' = .05" - .5" along with Eq. (3-32). The model parameters C and V obtained from WAFXMR4 and WAFXHR4 data sets are shown in Fig 5-15, Frame B.

5. Predictions for $p(i,\tau)$ in each stress region, based on the two-segment DCGA-SCGA, are computed using Eqs. (3-19), (3-23), (3-29) and (3-30).

6. From the predicted crack exceedance probability, $p(i,\tau)$ and the number of fastener holes in each stress region, the statistics for the number of cracks exceeding some crack sizes in the entire lower wing skin are computed using the Binomial distribution Eqs. (3-37) to (3-40) [e.g., 40].

7. Theoretical predictions are correlated with actual

Table 5-8. **Stress Levels and Number of Fastener Holes for F-16 Lower Wing Skin**

STRESS REGION	MAX. STRESS LEVEL (ksi)	NO. OF FASTENER HOLES
I	28.3	59
II	27.0	320
III	24.3	680
IV	16.7	469
V	28.4	8
VI	29.2	30
VII	32.4	8
VIII	26.2	8
IX	26.2	12
X	25.7	20
		1614

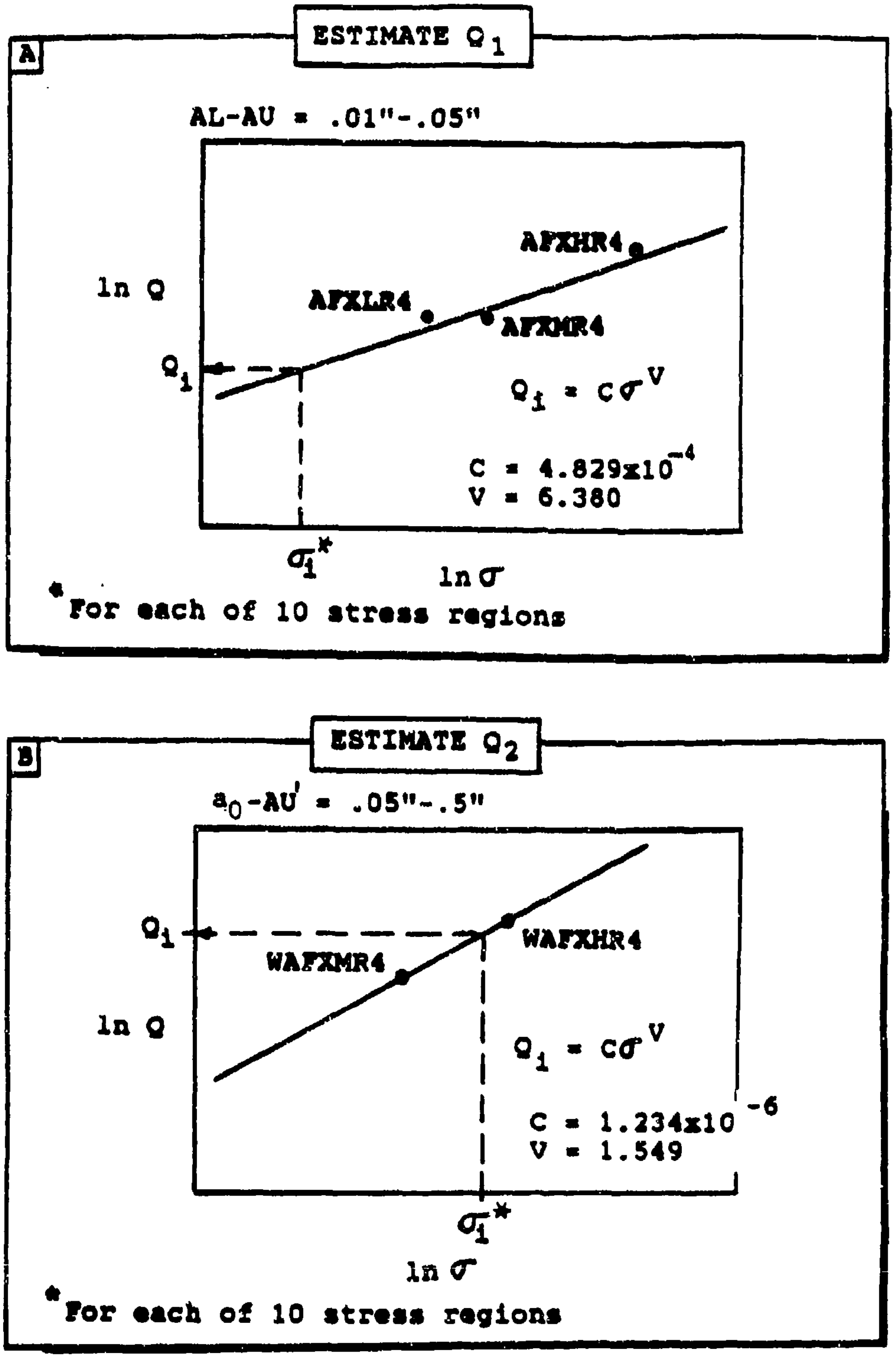


Figure 5-15. General Approach for Estimating Service Crack Growth Parameters Q_1 and Q_2.

test results from the F-16 durability test article. Results will be plotted in a useful format for evaluating the two-segment DCGA-DCGA and the DCGA-SCGA for durability analysis.

The same three fractographic data sets, i.e. AFXLR4, AFXMR4 and AFXHR4, were used to determine the EIFSD parameters in the previous [1,17,20-22] and present durability analyses for F-16 lower wing skin. However, different α and ϕ values for x_u = 0.03" are obtained in the present analysis due to the difference in the following: (1) fractographic crack size AL-AU ranges used for determining EIFSD and (2) fractographic data processing methods/screening considerations used. The resulting EIFSD parameter values are x_u = 0.03", α = 1.716 and ϕ = 6.308 (see Table 5-3).

In the previous durability analysis [1], terminal crack size dimensions in fastener holes were based on initial measurements of the fracture. In the present durability analysis, however, terminal crack sizes were based on the fractography. The final crack dimension based on the fractography are more accurate than the initial fracture surface measurements. There are small differences between the initial crack size dimensions and those based on the fractography. As a result of these differences, the experimental results for the average number of fastener holes/skin (for both wing skins) with a crack size > is 14.5 holes (fractography) versus 16.5 holes (initial measurements).

The F-16 durability test article was fatigue tested to flight hours using the F-16 1000 hour load spectrum. This preliminary spectrum included two 500-hour blocks. The F-16 400 hour loading spectrum has been used extensively in recent years for General Dynamics IRAD and CRAD research programs. This spectrum is slightly more severe than the F-16 hour spectrum but it doesn't apply to F-16 production aircraft. It is assumed for durability analysis purposes that the coupon fractographic results (i.e., AFXLR4, AFXMR4, AFXHR4, WAFXMR4 and WAFXHR4) based on the F-16 400 hour spectrum can be applied for the prediction of the F-16 durability test article.

The F-16 lower wing skins contain several cutouts. However, the present durability analysis/correlation covers only fatigue cracks in fastener holes.

5.2.1 Estimation of Service Crack Growth Parameters

The service crack growth parameters Q_1, Q_2 and σ_z were estimated for the small (i.e., AL-AU = 0.01" - 0.05") and large crack size region (i.e., a_0-AU$'$ = 0.05" - 0.5") for each of the ten stress regions. A general approach for estimating Q_1 and Q_2 is described in Fig. 5-15. In the small crack size region, Q_1 values for the AFXLR4, AFXMR4 and AFXHR4 data sets were obtained previously, Table 5-3 and Fig. 5-3. From these Q_1 values, the constants C and V in Eq.(3-32) were determined using a least-squares fit procedure (Fig. 5-3). Then, Q_1 values in each of the ten stress regions are computed from Eq. 3-32, and the results are shown in Table 5-9.

A similar approach to that described above was used for the large crack size region to estimate Q_2 for each of the ten stress regions. In this case, fractographic results of the WAFXMR4 and WAFXHR4 data sets (see Table 5-4) were used to estimate the constants C and V in Eq.(3-32). Results are shown in Table 5-9 and in Fig. 5-16.

In practice, suitable fractographic data may not be available to estimate Q_1 and Q_2. In such cases, an analytical crack growth program [e.g., 31,32] can be used to estimate the crack size versus time information needed to establish Q_1 and Q_2 for given durability analysis conditions (e.g., stress level, load spectrum, % bolt load transfer, etc.). Refer to

Table 5-9. Summary of Crack Growth Rate Parameters for Each Stress Region.

STRESS REGION	MAX. STRESS LEVEL (ksi)	NO. OF FASTENER HOLES	$Q_1 \times 10^4$(1) (1/HR.)	$Q_2 \times 10^4$(2) (1/HR.)
1	28.3	59	.884	2.187
2	27.0	320	.655	2.033
3	24.3	680	.334	1.727
4	16.7	469	.030	.966
5	28.4	8	.904	2.199
6	29.2	30	1.080	2.296
7	32.4	8	2.097	2.697
8	26.2	8	.541	1.941
9	26.2	12	.541	1.941
10	25.7	20	.478	1.884
		1614		

Notes: (1) Segment 1: AL-AU = 0.01" - 0.5"
$C_1 = 4.829 \times 10^{-14}$; $V_1 = 6.380$
(2) Segment 2: AL-AU = 0.05" - 0.5"
$C_2 = 1.234 \times 10^{-6}$; $V_2 = 1.549$

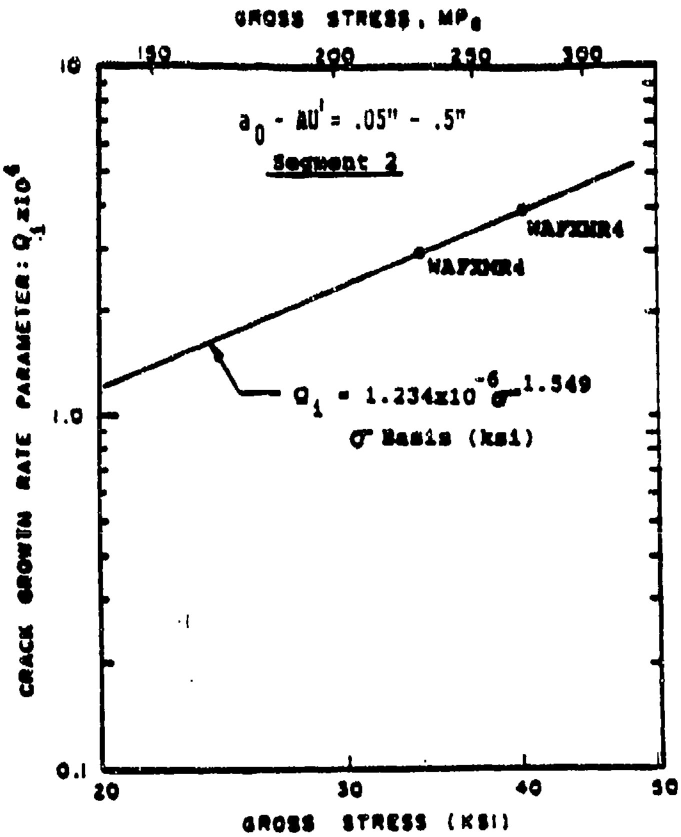


Figure 5-16. Crack Growth Rate Parameter Q Versus Gross Stress for Wide Specimen Data Sets (WAFXMR4 and WAFXHR4).

Section III herein and to Vols. I [2] and II [3] for further details.

5.2.2 Theoretical/Experimental Correlations

Probability of crack exceedance predictions $p(i, \tau)$ at $\tau = 16{,}000$ flight hours for five different crack sizes (i.e., x_1 = 0.03", 0.05", 0.1", 0.2" and 0.3") are shown in Table 5-10 for the two-segment DCGA-SCGA. The average number of fastener holes in each stress region, $\bar{N}(i, \tau)$ with a crack size greater than x_1 at $\tau = 16{,}000$ flight hours is also shown in this Table. The analysis for the DCGA-SCGA was conducted using $\sigma_z = 0.3$ (natural log basis), which is quite reasonable for countersunk fastener holes in 7475-T7351 aluminum [3,6].

Predictions for the average number of fastener holes in the entire lower wing skin with a crack size > x_1 at 16,000 flight hours, $\bar{L}(\tau)$, and the standard deviation, $\sigma_L(\tau)$, are shown in Table 5-11 for both the DCGA-DCGA (see Vol. II [3]) and the DCGA-SCGA. $\bar{L}(\tau)$ and $\sigma_L(\tau)$ values are computed based on the Binomial distribution, Eqs. (3-39) and (3-40). The tear-down inspection results based on the average of two lower wing skins are shown in the same table for comparison.

Theoretical predictions for the average number of fastener holes, $\bar{L}(\tau)$, with a crack size > x_1 at $\tau =$ flight hours in the entire lower wing skin are plotted in Fig. 5-17 for both of the two-segment crack growth approaches for comparison purposes. In this figure, the results for the DCGA-DCGA and the DCGA-SCGA are depicted by a solid curve and a dashed curve, respectively. Results for both approaches are identical for the crack size $x_1 \leq 0.05"$ in the first crack growth segment. The tear-down inspection results are shown in Fig. 5-17 as solid circles for comparison. These results reflect the average extent of damage for a lower wing skin

Table 5-10. Crack Exceedance Probability and Average Number of Fastener Holes with Crack Size Exceeding x_1 at τ=16,000 Flight Hours in Each Stress Region Based on DCGA-SCGA.

STRESS	x_1 = .03"		x_1 = .05"		x_1 = .1"		x_1 = .2"		x_1 = .3"	
REGION	$p(i,\tau)$	$\bar{N}(i,\tau)$	$p(i,\tau)$	$\bar{N}(i,\tau)$	$p(i,\tau)$	$\bar{N}(i,\tau)$	$p(i,\tau)$	$\bar{N}(i,\tau)$	$p(i,\tau)$	$\bar{N}(i,\tau)$
1	0.0739	4.36	0.0350	2.07	0.0183	1.08	0.0071	0.42	0.00348	0.20
2	0.0449	14.37	0.0145	4.64	0.00566	1.81	0.00126	0.40	0.000419	0.13
3	0.0144	9.79	0.0000683	0.05	0.0000066	0.004	0.0000066	0.004	0.0000066	0.004
4	0.000239	0.11	0.00	0.00	0.0000066	0.003	0.0000066	0.003	0.0000066	0.003
5	0.0768	0.61	0.0371	0.29	0.0196	0.16	0.00783	0.06	0.00392	0.03
6	0.103	3.09	0.0577	1.73	0.0335	1.00	0.0158	0.47	0.00894	0.27
7	0.287	2.29	0.225	1.80	0.160	1.28	0.104	0.83	0.0756	0.60
8	0.0326	0.26	0.00714	0.06	0.00187	0.01	0.000196	0.002	0.0000451	0.00
9	0.0326	0.39	0.00714	0.09	0.00187	0.02	0.000196	0.002	0.0000451	0.00
10	0.0264	0.53	0.00403	0.08	0.000621	0.01	0.000031	0.001	0.0000096	0.00
		35.80		10.81		5.377		2.192		1.237

Table 5-11. Statistics for Number of Fastener Holes with Crack Size Exceeding x_1 in F-16 Lower Wing Skin for Both DCGA-DCGA and DCGA-SCGA.

x_1 (IN.)	DCGA-DCGA		DCGA-SCGA		EXPERIMENTAL RESULTS (AVE.)
	$L(\tau)$	$\sigma_L(\tau)$	$L(\tau)$	$\sigma_L(\tau)$	
0.03	35.80	5.800	35.80	5.800	14.5
0.05	10.81	3.185	10.81	3.185	9.5
0.1	5.37	2.258	5.38	2.262	7.0
0.2	1.99	1.379	2.19	1.450	1.0
0.3	1.00	.977	1.24	1.097	0.5

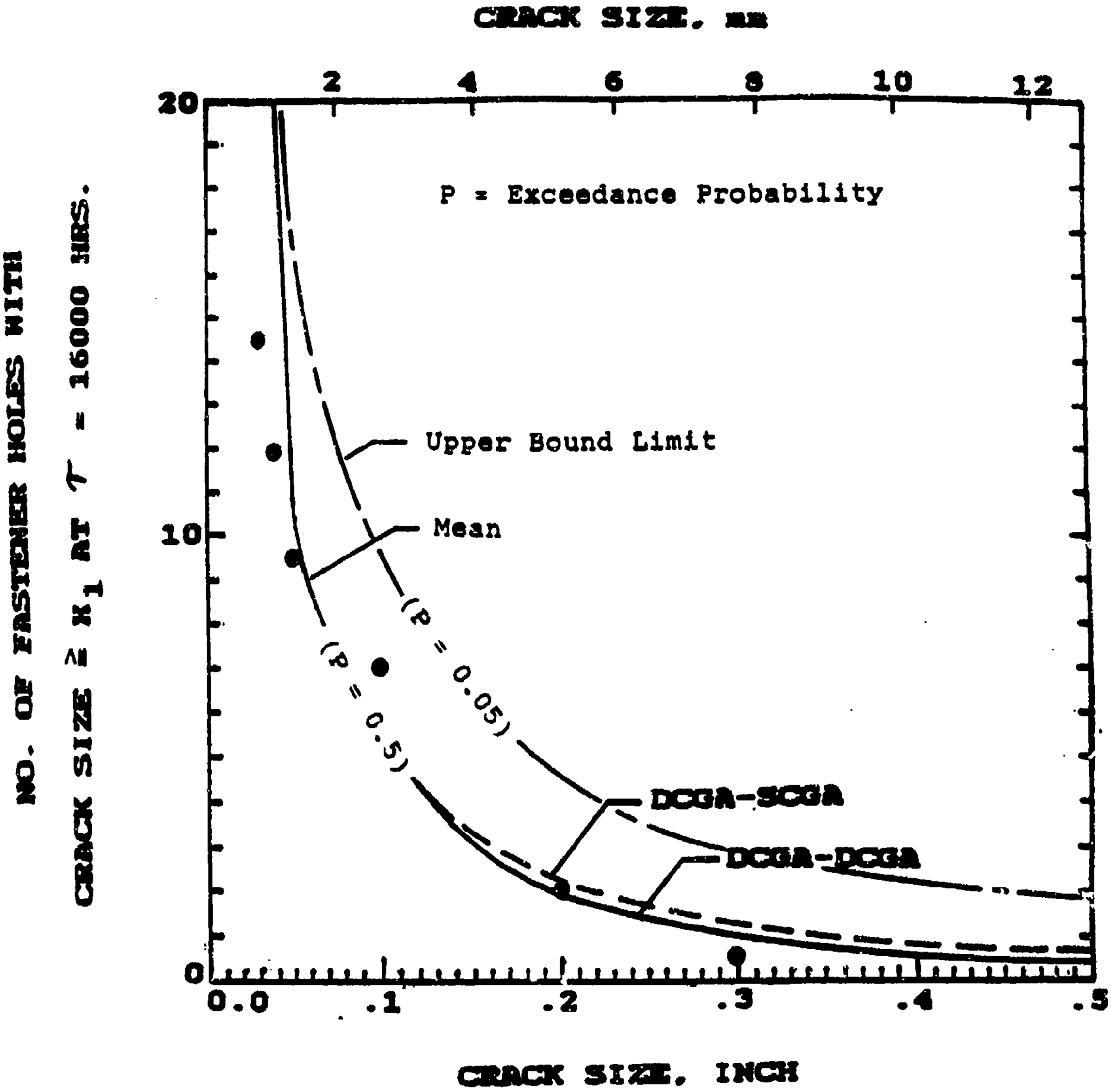


Figure 5-17. **Correlations between Theoretical Predictions and Experimental Results for Fighter Lower Wing Skin for Extent of Damage at τ = 16000 Flight Hours.**

based on the total extent of damage for both lower wing skins combined. Since the number of details in each stress region is large, it is reasonable to approximate the binomial distribution by the normal distribution. Hence, the predicted average extent of damage, $\bar{L}(\tau)$ corresponds to an exceedance probability of P = 0.5, see Fig. 5-17.

The extent of damage estimate for an exceedance probability of P = 0.05 is also plotted in Fig. 5-17 as a solid--dashed-solid curve (—— — ——). This curve represents the estimated upper bound limit for the extent of damage with an exceedance probability P = 0.05. It is computed from $\bar{L}(\tau)$ + $1.65\sigma_L(\tau)$ where $\bar{L}(\tau)$ and $\sigma_L(\tau)$ values are shown in Table 5-11 for the DCGA-SCGA.

To illustrate the usefulness of the extent of damage concept consider, for example, the extent of damage at x_1 = 0.3" in Fig. 5-17. The (predicted) probability is 50% (i.e., P=0.5) that 1.24 fastener holes will have a crack size exceeding x_1 = 0.3" ; whereas, the probability is 5% (i.e., P=0.05) that 3.05 fastener holes will have a crack size larger than x_1 = 0.3" at τ=16000 flight hours. Therefore, the durability analysis provides quantitative estimates of the extent of damage mean and upper bound limit. This type of information provides a physical description of the state of damage for a durability-critical component and a logical basis for estimating structural maintenance/repair requirements and costs.

5.2.3 Discussion of Results

The two-segment DCGA-SCGA has been demonstrated and evaluated using fractographic results for both coupon specimens and lower wing skins from a fighter aircraft. This approach was evaluated for fatigue cracking in both straight bore and countersunk fastener holes with clearance-fit fasteners. Results for two different two-segment durability analysis approaches (i.e., DCGA-DCGA and DCGA-SCGA) were compared for the lower wing skin demonstration. Both approaches are considered reasonable for evaluating functional impairment due to fuel leakage/ligament breakage in metallic aircraft structures. However, the DCGA-SCGA is recommended for durability analysis because predictions are more accurate and slightly more conservative than those based on the DCGA-DCGA. Extensive demonstrations for the DCGA-DCGA were given in Volume II [3].

The stress level in each stress region is important for crack growth predictions. Therefore, the stress analysis for durability-critical components should reflect appropriate finite element grid sizes to obtain the stress analysis accuracy desired for each stress region.

SECTION VI
DURABILITY ANALYSIS SOFTWARE

Software is available for implementing the advanced durability analysis method described in Section II of this Volume (IV) and in Volume I [2]. A comprehensive software user's guide is given in Volume V [24].

6.1 SOFTWARE DESCRIPTION

The advanced durability analysis software includes six programs in "GWBASIC". The purpose of each program is described in Table 6-1. All programs can be implemented on an IBM or IBM-compatible personal computer.

Software is available for plotting the fractographic data for any crack size or time range and/or durability analysis results for $F_{T(x_t)}(t)$, $p(i,\tau)$ or $F_{a(t)}(x)$. A plotting capability is available for the following durability analysis options: (1) DCGA, (2) DCGA-DCGA, and (3) DCGA-SCGA. Plots can be obtained with or without correlating data. Typical example plots are shown in Fig. 6-1.

6.2 SYSTEM REQUIREMENTS

The advanced durability analysis software is programmed in "GWBASIC". It runs on the IBM PC and IBM-compatible systems with the following minimum configuration:

Memory:	640K RAM
Operating System:	MS-DOS Version 2.0 or Later
Graphics Monitor:	Monochrome or Color
Disk Drive:	1 Double Sided Disk Drive
Printer:	IBM or IBM-Compatible Graphics Printer
Graphics Program:	Need Special "GRAPHICS" Program for Doing Screen Prints of Graphic Display

Table 6-1. Description of Durability Analysis Software for IBM or IBM-Compatible PC.

PROGRAM FILENAME	PURPOSE
"FRACT"	Save or read/print out fractographic data on 5 1/4" floppy disk
"SCREEN"	Study the character and quality of a fractographic data set (tabulate data and plot fractography)
"QSZAT"	Compute pooled Q and σ_z for a given fractographic data set
"WCIFQ"	Estimate EIFSD parameters for Weibull compatible distribution function
"PLOT"	Plot fractographic data and/or durability analysis results
"ANAL"	Make durability analysis predictions

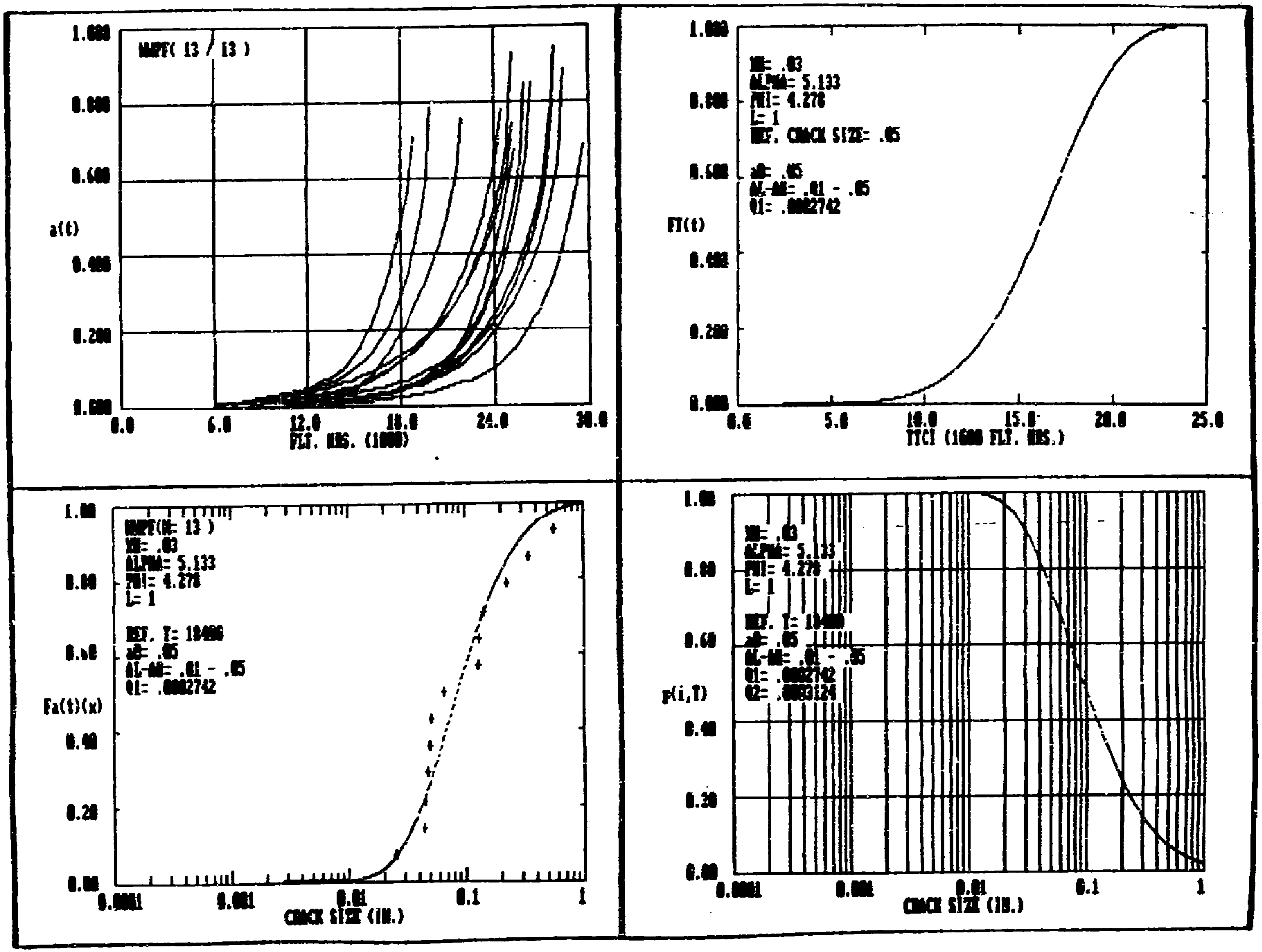


Figure 6-1. Example Plots for Durability Analysis Software "PLOT".

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

1. A comprehensive probabilistic durability analysis approach has been developed for metallic aircraft structures. It applies to the crack growth accumulation in any type of structural detail (e.g., fastener holes, cutouts, fillets, etc.). The approach has been verified for clearance-fit fastener holes in 7475-T7351 aluminum at two levels: (1) coupon specimens, and (2) full-scale aircraft structure. Very reasonable durability analysis results have been obtained, including damages due to both small cracks (e.g., $\leq$ 0.05") and large through-the-thickness cracks (e.g., $\geq$ 0.5").

2. It has been shown that the initial fatigue quality (IFQ) of both straight-bore and countersunk fastener holes with clearance-fit fasteners can be reasonably estimated using fractographic results from coupon specimens and that the IFQ can be represented by an equivalent initial flaw size distribution (EIFSD). Furthermore, it has been demonstrated that the IFQ of fastener holes in full-scale structures can be defined using coupon specimens.

3. The probabilistic durability analysis approach developed can be used to "quantify" structural durability in meaningful terms, such as: (1) probability of crack exceedance at any service time, (2) probability of functional impairment at any service time, (3) cumulative distribution of service time to reach any given crack size, (4) extent of damage, and (5) structural wearout rate. Since the probabilistic approach developed accounts for the fatigue crack growth accumulation in each structural detail susceptible to fatigue cracking in service, it is referred to as a "quanti-

tative durability analysis approach." The extent of damage prediction at a given service time is defined by the statistics, such as the average and standard deviation, of the number of structural details expected to exceed functional impairment crack size limits. This quantitative prediction provides an effective basis for evaluating functional impairment, economic life and structural wearout, and trade-offs as a function of the design and service variables.

4. The probabilistic durability analysis approach is a powerful "durability design tool." It gives the user new durability analysis capabilities and features not provided by the existing deterministic crack growth approach based on the "worst case" detail within a group of details. The probabilistic durability analysis method is not intended to completely replace the deterministic crack growth approach in the durability design process. The deterministic crack growth approach will continue to be a valuable tool for durability analysis - primarily during the preliminary design process. Since a deterministic crack growth analysis provides information only for the "worst case" detail within a group of details, it cannot provide the "extent of damage" type information for the entire population of structural details.

5. Equivalent initial flaw sizes (EIFSs) are determined by back-extrapolating fractographic results. Since the fractographic data depends on the testing conditions (e.g., load spectrum, fastener holes, cutout, etc.), EIFSs are not strictly "generic." However, EIFSD parameters can be estimated for different fractographic data sets using the data pooling and statistical scaling procedures. It has been conclusively shown that the EIFSD based on given fractographic data sets can be used to obtain very reasonable durability analysis predictions for the other data sets and full-scale aircraft structure for clearance-fit fastener holes (both straight-bore and countersunk) in 7475-T7351 aluminum. It

should be clear that an EIFSD does not necessarily contain the "rogue flaw."

6. When an EIFSD is grown forward to a selected service time, the service crack growth should be consistent with the "basis" for the EIFSs. Therefore, the analytical crack growth program used [e.g., 31,32] should be "tuned" or "curve fitted" to the EIFS master curves reflected in the EIFSD.

7. Probabilistic-based durability analysis methods [2, 3,5-7] are now sufficiently developed and demonstrated for immediate applications to metallic airframes. An updated durability design handbook and software for an IBM or IBM-compatible PC are available for implementing the advanced durability analysis.

8. A "natural fatigue crack" data base for estimating the initial fatigue quality of structural details can be acquired as a part of the Aircraft Structural Integrity Program (ASIP) test plan. For example, by not preflawing structural details in test specimens, "natural fatigue crack" data can be obtained--thereby satisfying data requirements for both durability and damage tolerance. Additional testing and fractographic evaluations, beyond the normal ASIP effort, may be needed to define IFQ, depending on the desired confidence level and circumstances. IFQ data requirements can be readily incorporated into the ASIP test plan to minimize the cost and time for acquiring the requisite data base.

9. The stress level for each stress region is important for crack growth predictions. Therefore, the stress analysis for durability-critical components should reflect appropriate finite element grid sizes to obtain the desired stress analysis accuracy for each stress region.

10. Probabilistic durability analysis methodologies de-

veloped can be extended to establish the optimal inspection/repair/replacement/proof test maintenance for life management of metallic aircraft structure. The extension can be made based on some fundamental research efforts appearing in the literature [e.g., 18, 35-36, 50-58].

7.2 RECOMMENDATIONS

1. The advanced durability analysis method developed under this program should be used for future durability analyses for metallic airframes. Structural durability can now be quantitatively accounted for in the durability design process.

2. Recommendations for durability analysis are as follows: (1) define the equivalent initial flaw size distribution (EIFSD) using fractographic data in the small crack size region (e.g., 0.01"-0.05"), (2) use fractographic data pooling procedure and statistical scaling technique to estimate the EIFSD parameters in a "global sense" for a "single hole population" basis, and (3) use the two-segment deterministic-stochastic crack growth approach (DCGA-SCGA) to predict the extent of damage in the entire durability critical component; the two-segment deterministic crack growth approach (DCGA-DCGA) is also reasonable but it is slightly less conservative than the DCGA-SCGA.

3. The recommended changes in Air Force philosophy and durability design requirements described in Volume IV [4] should be adopted. This will allow the full potential of the probabilistic durability analysis approach to be utilized in the design and analysis of future metallic aircraft structures.

4. The advanced durability analysis approach developed under this program should be investigated for other structur-

al details and considerations. For example, the life enhancement effects of fastener hole cold working, interference fit fasteners, press fit bushings, etc., on initial fatigue quality should be investigated. Similarly, the initial fatigue quality of structural details, such as cutouts, lugs, fillets, etc., should be investigated. Suitable test specimens should be developed and standardized for acquiring initial fatigue quality data for those structural details to be included in the durability analysis.

5. Future ASIP test plans should be designed to provide data for initial fatigue quality, durability and damage tolerance. Selected fatigue tests should be conducted using specimens without intentional preflaws so that "natural fatigue crack" data can be obtained. This approach should be used to minimize cost and time for acquiring the requisite IFQ data base.

6. The meaning and limitations of EIFSs and an EIFSD must be emphasized. In particular, all EIFSs should be grown forward consistent with the basis for the EIFSD. The EIFSD should not be grown forward using an analytical crack growth program without tuning and considering the basis for the EIFS.

7. All aerospace contractors should use the same method to define EIFSs for different materials and structural details so that compatible EIFSs can be obtained. The "Qa(t) model" (Eq. (3-2) with b=1) is reasonable for determining EIFSs. This model or some other suitable model should be used to standardize the way EIFSs are determined. Then, for a given fractographic data set, fractographic crack size range (AL-AU) and the same analysis procedure, all contractors will obtain the same EIFSs. By standardizing the way EIFSs are determined, EIFSs from various sources can be directly compared - thereby providing a means for cataloging

and utilizing existing data from various sources to estimate the initial fatigue quality of structural details.

8. Initial fatigue quality and the initial flaw size distribution vary with respect to material, type of fastener hole, structural details, manufacturing processes, etc. For example, the statistical dispersion of EIFSD for countersunk holes is significantly larger than that for the EIFSD for straight-bore holes for clearance-fit fasteners in the same material in which the holes were drilled using comparable methods.

9. The probabilistic durability analysis approach should be investigated for discriminating "quality" at three levels: (1) material, (2) manufactured detail, and (3) component. Of particular interest is the following question: "How does improvement in initial material quality translate into improvement in life of actual aircraft components?" This research can be built on the advancements made under this program and the work conducted by ALCOA [e.g., 48,49].

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DEFINITIONS

The technical terms defined herein supercede those given in Volume I, AFWAL-TR-86-3017 (2). New terms have been added and selected Volume I terms have been revised. Should any questions arise, the definitions herein should be used.

DEFINITIONS

1. Combined Least Square Sums Approach (CLSSA) - the least square sums for individual fractographic data sets are combined to estimate the EIFSD parameters in a "global sense." This approach is used in conjunction with the data pooling philosophy.

2. Compatible Equivalent Initial Flaw Size Distribution Function - this is a distribution function for equivalent initial flaw sizes (EIFS) which is derived using a physically meaningful cumulative distribution of time-to-crack initiation (TTCI) function and a suitable deterministic crack growth law.

3. Crack Size - is the length of a crack in a structural detail in the direction of crack propagation.

4. Cumulative Distribution of Service Time ($F_{T(x_1)}(\tau)$) - is defined as the probability that the service time $T(x_1)$ to reach a crack size x_1 is shorter than τ. It is equal to the probability that the crack size $a(\tau)$ at service life τ will exceed x_1, which is simply the probability of crack exceedance, i.e.,

$$F_{T(x_1)}(\tau) = P[T(x_1) \leq \tau] = P[a(\tau) \leq x_1] = p(i, \tau)$$

5. Data Pooling - is a concept for estimating the EIFSD parameters using one or more fractographic data sets in a "global sense." A data pooling procedure is used to increase the sample size for determining the EIFSD parameters.

6. <u>Deterministic Crack Growth Approach (DCGA)</u> - Crack growth parameters are treated as deterministic values resulting in a single value prediction for crack length.

7. <u>Durability</u> - is a quantitative measure of the structural resistance to fatigue cracking under specified service conditions. Structural durability is concerned with the prevention of functional impairments due to: (1) excessive cracking and (2) fuel leakage/ligament breakage. Excessive cracking is concerned with relatively small subcritical crack sizes (e.g., $\leq$ 0.05") which affect functional impairment, structural maintenance requirement and life-cycle-costs. Such cracks may not post an immediate safety problem. However, if the structural details containing such cracks are not repaired, economical repairs cannot be made when these cracks exceed a limiting crack size. Functional impairment due to fuel leakage/ligament breakage is typically concerned with large through-the-thickness cracks (e.g., 0.50"-0.75"). Although such cracks are usually subcritical, they affect the residual strength, fleet readiness, and may require increased maintenance action.

8. <u>Durability Analysis</u> - is concerned with quantifying the extent of structural damage due to fatigue cracking for structural details (e.g., fastener hole, fillet, cutout, lug, etc.) as a function of service time. Results are used to ensure design compliance with Air Force's durability design requirements.

9. <u>Economic Life</u> - is that point in time when an aircraft structure's damage state due to fatigue, accidental damage and/or environmental deterioration reaches a point where operational readiness goals cannot be preserved by economically acceptable maintenance action.

10. Economic Life Criteria - are guidelines and formats for defining quantitative economic life requirements for aircraft structure to satisfy U. S. Air Force Durability design requirements. The economic life criterion provides the basis for analytically and experimentally ensuring design compliance of aircraft structure with durability design requirements. Two recommended formats for economic life criteria are:

- o probability of crack exceedance
- o cost ratio: repair cost/replacement cost

11. Economic Repair Limit - is the maximum damage size that can be economically repaired (e.g., repair 0.03"-0.05" radial crack in fastener holes by reaming hole to next size).

12. Equivalent Initial Flaw Size (EIFS) - is an artificial crack size which results in an actual crack size at an actual point in time when the initial flaw is grown forward. It is determined by back-extrapolating fractographic results. It has the following characteristics: (1) an EIFS is an artificial crack assumed to represent the initial fatigue quality of a structural detail in the as-manufactured condition whatever the source of fatigue cracking may be, (2) no direct relationship to actual initial flaws in fastener holes such as scratches, burrs, microdefects, etc., and it cannot be verified by NDI, (3) a universal crack shape in which the crack size is measured in the direction of crack propagation, (4) it's in a fracture mechanics format but EIFSs are not subject to linear elastic fracture mechanics (LEFM) laws or limitations, such as the "short crack effect" [e.g., 41-47], (5) it depends on the fractographic data, the fractographic crack size range for the back extrapolation, and the crack

growth rate model used, (6) it must be grown forward in a manner consistent with the basis for the EIFS, and (7) EIFSs are not unique - a different set is obtained for each crack growth law used for the back- extrapolation.

13. Equivalent Initial Flaw Size Distribution (EIFSD) - is used to represent the initial fatigue quality variation of a structural detail. An EIFS is a random variable, and the EIFSD statistically describes the EIFS population. The EIFSD does not necessarily contain the "rogue flaw."

14. EIFS Master Curve - is a curve (e.g., equation, tabulation of a(t) vs. t or curve without prescribed functional form) used to determine the EIFS value at t=0 corresponding to a given TTCI value at a specified crack size. Such a curve is needed to determine the EIFS distribution. The EIFS master curve depends on several factors, such as the fractographic data base, the fractographic crack size range used, the functional form of the crack growth equation used in the curve fit, etc. (Ref. EIFS).

15. Extent of Damage - is a quantitative measure of structural durability at a given service time. For example, the number of structural details (e.g., fastener holes, cutouts, fillets, etc.) or percentage of details exceeding specified crack size limits with a certain probability. Crack length is the fundamental measure for structural damage. The predicted extent of damage is compared with the specified economic life criterion for ensuring design compliance with U. S. Air Force durability requirements.

16. Generic EIFS Distribution - An EIFS distribution is "generic" if it depends only on the material and manufacturing/fabrication processes. An EIFSD is not strictly "generic" because it is based on fractographic results which reflect given conditions (e.g., load spectra). For durability analysis, an EIFSD is established using the fractographic results for one or more data sets, and the resulting EIFSD is justified for a different set of conditions.

17. Initial Fatigue Quality (IFQ) - characterizes the initial manufactured state of a structural detail or details with respect to initial flaws in a part, component, or airframe prior to service. Actual initial flaws in a fastener hole are typically random scratches, burrs, microscopic imperfections, etc. Such flaws are not cracks per se like those associated with linear elastic fracture mechanics. The IFQ is represented by an equivalent initial flaw size distribution (EIFSD).

18. Probability of Crack Exceedance ($p(i,\tau)$) - refers to the probability that a crack in the ith stress region will exceed a specified crack size, x_1, at a given service time, τ. It can be used to quantify the extent of damage due to fatigue cracking in fastener holes, cutouts, fillets, lugs, etc.

19. Reference Crack Size (a_0) - This is the specified crack size in a detail used to reference TTCI s.

20. Service Crack Growth Master Curve (SCGMC) - SCGMC is a curve, expressed by equation or tabulation of a(t) versus t, used to grow EIFSs forward in order to determine the crack size distribution at any service time. The SCGMC must be consistent with the basis for the EIFS distribution.

21. Service Time to Reach Any Crack Size x_1 - This term describes the time, $T(x_1)$, to reach any specified crack size x_1. In this context, the crack size x_1 can be associated with either the "crack initiation" or the "crack propagation" process. The time-to-crack-initiation (TTCI) term is restricted to crack sizes associated with the crack initiation process, where $x_1 = a_0$ (reference crack size for TTCIs).

22. Statistical Scaling - is used to account for the inhomogeneous fractographic data, in particular fractographic data associated with the largest flaw per specimen with holes.

23. Stochastic Crack Growth Approach (SCGA) - an approach which directly accounts for the crack growth rate dispersion in the durability analysis.

24. Structural Detail - is any element in a metallic structure susceptible to fatigue cracking (e.g., fastener hole, fillet, cutout, lug, etc.).

25. Time-To-Crack-Initiation (TTCI) - is the time or service hours required to initiate a specified (observable) fatigue crack size, a_0, in a structural detail (with no initial flaws intentionally introduced).

26. <u>TTCI Lower Bound Limit (ϵ)</u> - is a minimum value for time-to-crack initiation with a reference crack size a_0. It depends on the reference crck size a_0 for TTCI; the larger a_0, the larger ϵ.

27. <u>Upper Bound EIFS Limit (x_u)</u> - defines the largest EIFS in the initial fatigue quality distribution. Constraints on x_u for fatigue holes: largest EIFS in data set $\leq x_u$ (e.g., 0.03"-0.05").

ACRONYMS

ADA	=	Advanced Durability Analysis
ASIP	=	Aircraft Structural Integrity Program
CLSSA	=	Combined Least Square Sums Approach
DADTA	=	Durability and Damage Tolerance Assessment
DCGA	=	Deterministic Crack Growth Approach
EIFS	=	Equivalent Initial Flaw Size
EIFSD	=	Equivalent Initial Flaw Size Distribution
FHQ	=	Fastener Hole Quality
HEIFS	=	Homogeneous EIFS
IFQ	=	Initial Fatigue Quality
LEFM	=	Linear Elastic Fracture Mechanics
LT	=	Load Transfer Through the Fastener
MM	=	Method of Moments
NDE	=	Non Destructive Evaluation
NDI	=	Non Destructive Inspection
NLT	=	No Load Transfer Through the Fastener
SCGA	=	Stochastic Crack Growth Approach
SCGMC	=	Service crack growth master curve
SSE	=	Sum Squared Error
TSE	=	Total Standard Error
TTCI	=	Time-to-Crack Initiation

LIST OF SYMBOLS

a	=	Crack Size
a_0	=	Reference crack size for given TTCIs
$a(0)$	=	EIFS = Crack size at $t=0$
$a(t)$	=	Crack size at any service time t
$a(t)$, $a(t_1)$, $a(t_2)$	=	Crack size at time t, t_1 and t_2, respectively
$a(T)$	=	Crack size at service time T
$a(\tau)$	=	Crack size at any service time τ
AL, AU	=	Lower and upper bound fractographic crack size, respectively, used to define the EIFSD parameters. Also used in conjunction with the SCGMC to define crack size limits for the small crack size region.
AU'	=	Upper bound crack size limit for the large crack size region
b, Q	=	Crack growth parameters in the equation $\frac{da(t)}{dt}=Q[a(t)]^b$. Used in conjunction with the IFQ model.
b_1, Q_2	=	Service crack growth rate parameters in the equation $da/dt = Q_1(a)^{b_1}$ associated with the one-segment DCGA or 1st segment of the two-segment approach.

b_2, Q_2	=	Service crack growth rate parameters in the equation $da/dt = Q_2(a)^{b_2}$ for segment two of the two-segment DCGA.
c	=	$b - 1$; Used in conjunction with the IFQ model when the crack growth law, $\frac{da(t)}{dt} = Q[a(t)]^b$ is used and $b > 1.0$.
$\frac{da(t)}{dt}$	=	Crack growth rate as a function of time
$f_X(u)$	=	Probability density function of X.
$F_{a(0)}(x)$	=	EIFS cumulative distribution function for a "single hole population."
$F_{a_\ell(0)}(x)$	=	Cumulative distribution of EIFS based on the largest fatigue crack per test specimen with ℓ holes.
$F_{a_{\ell_i}(0)}(x_{ij})$	=	Subscripted notation used for $F_{a_\ell(0)}(x)$ in conjunction with data pooling, where: j denotes the jth crack in the ith data set.
$F_{a(t)}(x)$	=	Cumulative distribution of crack size a(t) at any service time t.
$F_{a_\ell(t)}(x)$	=	Cumulative distribution of crack size $a_\ell(t)$ at any service time t for the largest fatigue crack per test specimen with ℓ holes.

$F_T(t)$	=	TTCI cumulative distribution function
$F_{T_{\ell_i}}(t)$	=	Cumulative distribution of minimum TTCIs based on the largest fatigue crack per test specimen with ℓ_i holes.
$F_{T_{\ell_i}}(t_{ij})$	=	Subscripted notation used for $F_{T_\ell}(t)$ in conjunction with data pooling, where: j = jth TTCI value in the ith data set.
$F_{T(x_1)}(\tau)$	=	Cumulative Distribution of service time $T(x_1)$ to reach a crack size x_1.
$G(x_1; \tau \mid X=u)$	=	Initial flaw size corresponding to crack size x_1 at time τ with X = u.
ℓ	=	No. of fastener holes per test specimen.
$L(\tau)$, $\bar{L}(\tau)$	=	Total and average number of details, respectively, in the entire component having a crack size $\geq x_1$ at any service time τ.
LT	=	Load transfer through the fastener.
m	=	Number of stress regions (or total number of fatigue cracks in a data set, Eqs. (3-33),(3-34).
M	=	Total number of EIFS data sets used to estimate the EIFSD parameters.
N_i	=	Number of TTCI or EIFS values for the ith data set used in conjunction with the combined least square sums approach.

$N(i,\tau)$, $\bar{N}(i,\tau)$	=	Total and average number of details, respectively, having a crack size exceeding x_1 at any service time τ
$p(i,\tau)$	=	Probability that a detail in the ith stress region will have a crack size $>x_1$ at the service time τ
Q_i	=	Crack growth rate parameter (see Eq.(3-6) for the ith fractographic data set or "pooled Q" value. It is used to determine EIFSs.
Q_j	=	Crack growth rate parameter (see Eq.(3-5) for the jth fatigue crack in a fractographic data set.
t, t_1, t_2	=	Flight hours at t, t_1, t_2, respectively.
T, TTCI	=	Time-to-crack-initiation
$T(x_1)$	=	Service time to reach any crack size x_1.
u	=	A particular value of X (lognormal random variable).
x	=	Crack size
x_1	=	Crack size used for $p(i,\tau)$ predictions or reference crack size for $F_{T(x_1)}(\tau)$ predictions.

x_u	=	Upper bound limit for EIFS
X	=	Lognormal random variable with a median of 1.0.
X_{ij}	=	$\ln \ln(x_u/x_{ij})$
$Y_{1i}(\tau)$	=	An EIFS value in the EIFSD corresponding to a crack size x_1 at time τ in the ith stress region.
Y_{ij}	=	$\ln\{-(1/\ell_i)\ln[\frac{j}{N_i+1}]\}$
Z	=	Log X
$\Gamma(\ )$	=	Gamma function
c, v	=	Empirical constants in the equation: $Q_i = c\sigma_i^v$, where σ_i = stress
σ_z	=	Standard deviation of Z = Log X.
τ	=	A particular service time
α, ϕ	=	Weibull compatible shape and scale EIFSD parameters, respectively
γ	=	Q_1/Q_2

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